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FULL-SCALE CARBON ADSORPTION

APPLICATIONS STUDY

FINAL REPORT

by

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Six full-scale, fixed-bed carbon adsorption systems were tested for vapor-phase volatile organic compound removal efficiency. Solvents used in the systems included methyl ethyl ketone, isopropyl acetate, tetrahydrofuran and toluene. One year after the first tests, repeat testing was performed on four of the original six sites. Removal efficiencies of three adsorption systems were lower during the repeat testing. However, carbon age was not the primary factor involved.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Hazardous Waste Engineering Research Laboratory assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report presents the results of field testing of six full-scale carbon adsorption systems used to recover a variety of organic solvents (tolune, MEK, isopropyl acetate, THF and cyclohexanone). This study was initiated to investigate the changes, if any, in operating efficiency of full-scale carbon adsorption systems with time. The results should be of interest to regulatory agencies and industrial sources involved in VOC emissions control and solvent recovery.

Requests for further information regarding this study should be directed to the Project Officer at the Hazardous Waste Engineering Research Laboratory, Cincinnati.

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ABSTRACT

This report details the results of field testing for six (6) full-scale, fixed-bed carbon adsorption systems. These carbon units are used to recover a variety of vaporized organic solvents such as toluene, MEK, THF, isopropyl acetate, MIBK and cyclohexanone. The six plants were spread throughout three industry sectors: rubberized fabric manufacturing, magnetic tape manufacturing and flexible packaging manufacturing. The six plants were tested for a two-week period and then four of the six plants were retested in a similar manner approximately 18 months later. The repeat testing was designed to evaluate the long-term degradation of the carbon beds.

The test results showed that of the six systems tested, four had useful carbon lives of four to six years or longer. One plant had a useful carbon life of only a few months. In general, volatile organic compound (VOC) reduction performance of the fixed-bed system for the six plants was greater than 95 percent. However, system malfunctions can greatly reduce this performance level.

As a final part of the study, a computer model was examined as to its capability in predicting the VOC reduction performance of carbon bed systems. Although the results were encouraging, more development work is needed to refine the model.

This report was submitted in fulfillment of Work Assignment 2, Contract No. 68-03-3038 by Hazardous Waste Engineering Research Laboratory, Office of Research and Development under the sponsorship of the U. S. Environmental Protection Agency. This report covers a period from March 1981, to March 1984, and work was completed as of May 1984.

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SECTION 1

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is currently evaluating the environmental and health impacts of volatile organic compound (VOC) emissions from a variety of industrial sources. As part of this effort, Radian Corporation has conducted a program (EPA Contract No. 68-03-3038) to evaluate the performance of full-scale, vapor-phase carbon adsorption VOC control systems used for solvent recovery. The program has focused on the field performance testing of several fixed-bed, steam-regenerated carbon adsorption systems used in the rubberized fabric, magnetic tape, and flexible packaging industries. Further discussion of program incentives, objectives, and approach are presented in the remainder of this section.

Program results and conclusions are summarized in Section 2, with emphasis placed upon defining comparative performance of the tested systems and major factors affecting performance. Carbon adsorption theory is reviewed in Section 3, providing the technical background for subsequent evaluations of system operating parameters and performance. Section 4 presents a review of typical surface coating operations and carbon adsorption/solvent recovery applications within the surface coating industry. The testing methodology developed for this program is outlined in Section 5, and results of the carbon adsorption performance testing conducted at six test sites (Plants 1 through 6) are presented in Sections 6 through 11. A comparative analysis of the performance data from the six tested systems follows in Section 12. Section 13 summarizes the results of a carbon adsorption modeling effort conducted during the program. Results of the model validation for actual test conditions at several of the test plants are provided.

BACKGROUND

Emissions of VOCs are of concern primarily because of their contribution to localized atmospheric pollution, in particular as related to the complex mixture of noxious airborne compounds referred to as "smog." The chemical mechanisms of smog formation are complex, but the general relationships and causes are understood. In general, the formation of smog results from photochemical reactions between VOCs and nitrogen oxides in the presence of sunlight to form oxidants. These oxidants, of which ozone is an example, include (or participate in reactions to form) a variety of noxious compounds, such as aldehydes and peroxyacetyl nitrate (PAN). The presence of these compounds in the atmosphere has been shown to reduce visibility (due to condensation of the compounds to form aerosol particles) and to cause eye irritation, respiratory distress, nose and throat irritation, and vegetation damage. These conditions are prevalent in heavily industrialized urban areas, although VOCs emitted in rural areas can also contribute to smog formation if they are transported in the atmosphere to areas where heavy smog exists (1-4). In addition, certain VOCs contribute to potential health problems in the workplace, due to their toxicity or carcinogenicity (5,6).

VOC Emissions from Surface Coating Facilities

Surface coating involves the application of a material to a paper, plastic, metal, fabric, or wood substrate to form an intermediate or end-product with certain desired characteristics. Often the coating material is suspended or dissolved in an organic solvent and is applied to the substrate in a fluid state. Emissions of solvent vapors or volatile organic compounds (VOCs) occur during various processing steps, but primarily from the drying or curing of the wet coated substrate. The surface coating industry is discussed in more detail in Section 4.

It has been estimated that the solvent emissions from the surface coating industry account for approximately 10 percent of the 17,000,000 tons per year of man-made non-methane VOC emissions in this country (5,7). Therefore, surface coating ranks fourth as a VOC source behind fossil fuel handling and refining, solid waste disposal, and open sources (e.g., agricultural burning). It is estimated that over 80 percent of the VOC emissions from the surface coating industry are controllable (5). Current available control technologies include coating process modifications, the use of low-solvent or solvent-free coatings, and the use of add-on control systems, such as carbon adsorption and incineration, either thermal or catalytic.

Regulatory Activity

The surface coating industry has become the subject of increasing regulatory activity because: (1) the industry contributes significantly to national and localized VOC emission levels and (2) it has been determined that a significant portion of the VOC emissions can be controlled in an economically and environmentally acceptable manner.

Initial regulation of VOC emissions from surface coating facilities was imposed by local air pollution regulatory agencies, the most notable being Rule 66--Organic Solvents, adopted by the Los Angeles Air Pollution Control

District. Rule 66 was a technology-forcing regulation which gave preferential treatment to users of so-called "non-photochemically reactive" solvents. Other local and state agencies adopted VOC regulations similar to Rule 66 on an as-needed basis.

The passing into law of the Clean Air Act and its 1977 amendments provided more systematic strategies for federal and state regulation of existing and new sources of VOC (and other) emissions (8). For regulation of existing sources, the U.S. EPA issued a series of documents referred to as Control Technique Guideline (CTG) reports. The CTG reports were designed to assist state agencies in the drafting of regulations, referred to as State Implementation Plans (SIP), most of which are now in place. For regulation of new sources, the federal EPA assumed the responsibility for drafting of applicable regulations, referred to as New Source Performance Standards (NSPS) or, in the case of toxic materials, National Emission Standards for Hazardous Air Pollutants (NESHAP). NSPS regulations pertaining to new surface coating facilities that have been promulgated (finalized) include those for metal furniture, automobiles and light-duty trucks, graphic arts (publication rotogravure printing), large appliances, metal coil, beverage cans, and pressure sensitive tapes and labels (8-15). NSPS are currently being considered or drafted for the magnetic tape, rubberized fabric, and flexible packaging coating industries. The NSPS which have been proposed and promulgated are generally based on the use of low-solvent or solvent-free type coatings or the use of add-on control technology.

Carbon Adsorption as a VOC Control Option

Add-on VOC control devices, such as carbon adsorption or incineration systems, have been widely used in the surface coating industry because they are readily available and generally do not adversely affect the coating process or product quality. In general, incineration of solvent vapors is selected for surface coating operations that are subject to VOC emission regulations but use a solvent formulation for which recovery is technically impractical. By comparison, the selection of carbon adsorption for VOC control is governed by economic, as well as regulatory, incentives. In particular, carbon adsorption/solvent recovery is suited for applications having a solvent formulation that is relatively expensive and/or easily recovered (i.e., either comprised of a single solvent or of several components that can be easily separated or reused as a mixture).

PROGRAM OBJECTIVE

Inherent in any cost-effectiveness evaluation of a carbon adsorber installation is some decision on the effective life of the carbon. The Agency was unable to find substantative data to reflect the effect of irreversible fouling that may take place as a result of impurities or by-products of some industrial operations. This study was initiated to investigate the change, if any, in efficiency of the carbon bed with time.

As previously mentioned, carbon adsorption-based solvent recovery is a commonly used VOC control technology in the surface coating industry. Economic and/or regulatory incentives contribute to its wide application. However, there are limited data available which determine performance of full-scale activated carbon systems, particularly in relation to the effects of carbon service life and to VOC removal efficiency. Therefore, in order to evaluate the VOC control performance, the following program objectives were established: (1) to determine the effects of carbon service life on long-term system performance. The approach selected to fulfill these program objectives is described in the following subsection, (2) to test the adsorbers under a variety of operating conditions, and (3) to select a model that represents adsorption and to compare field data to the model's prediction.

PROGRAM APPROACH

The following tasks were defined to evaluate the performance of carbon adsorption systems in accordance with the program objectives:

- Engineering evaluation of performance parameters--analysis of available literature to identify the theories of the adsorption mechanism, characteristic operating parameters, and existing long-term performance data (Sections 3 and 4);

- Development of testing strategy--selection of test methods and overall testing approach based on the identified performance parameters (Section 5);

- Identification of test sites--identification, screening, and selection of representative carbon adsorption systems in the rubberized fabric, magnetic tape, and flexible packaging industries (Section 5);

- Performance of on-site testing--comprehensive field testing of the selected adsorption systems, followed by repeat testing at several of the sites approximately 18 months later for determination of performance degradation, if any, due to carbon aging (Sections 6 through 11);

- Evaluation of test data--analysis of performance and cost data and identification of relationships between VOC control efficiency and system characteristics and operating parameters (Section 12);

- Modeling of carbon adsorption performance--selection and validation of an available carbon adsorption/regeneration model using the measured test data (Section 13); and,

- Development of conclusions and recommendations--development of conclusions regarding the effects of carbon life and other parameters on carbon adsorption performance and presentation of recommendations regarding additional research topics (Section 2).

The results of the foregoing tasks are presented in the remainder of this final report.

EPA guidelines for quality assurance/quality control (QA/QC) were followed as identified in the QA Project Plan for this program. The QA/QC procedures specifically apply to the field testing portion of the overall project. The results of these investigations have been reported in separate documents to the EPA (Industrial Environmental Research Laboratory - Cincinnati) and indicate that the data are adequate to support the findings of this study.

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SECTION 2

SUMMARY AND RECOMMENDATIONS

Solvent emissions from surface coating operations account for a significant portion of the man-made nonmethane volatile organic compound (VOC) emissions in the United States. The surface coating industry consists of a wide variety of manufacturing operations that apply a coating material on a continuous surface to produce a desired intermediate- or end-product. The coating is often borne or dissolved in organic solvents that are volatilized from the substrate as it is dried, resulting in VOC emissions. To abate the VOC emissions, the coating facilities often use add-on control technologies such as thermal or catalytic incineration or activated carbon adsorption.

In this study, the use of activated carbon technology is examined with regard to theory and applications for the surface coating industry. The program features performance testing of full-scale, fixed-bed, steam-regenerated carbon systems. The rubberized fabric, magnetic tape, and flexible packaging industries are used as specific examples of carbon adsorption applications in the surface coating industry. Particular emphasis is placed on measuring VOC removal efficiency of the active bed system and estimating carbon life for each application. The results of this study are summarized in this section of the report.

THEORY AND APPLICATIONS

Over the past 50 years, significant research has been undertaken in academia and industry to achieve both fundamental and practical understanding of the adsorption of organic materials on active carbons. Several theories

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have been proposed to analytically predict activated carbon capacities. Prominent among these is the Polyani potential theory (with later revisions by Dubinin). With the potential theory, the adsorption capacity of a particular carbon-solvent pair can be used to predict the adsorption capacities of that particular carbon for numerous other organic compounds.

Most of the research to-date has been for single organic components on a single carbon. In actual application, most full-scale industrial systems use multicomponent solvents. However, theoretical derivations for multicomponent systems are complex and difficult to use. Although multicomponent theories have been developed, often based on concepts and data for single component theories, they are not as well developed or understood as the single component theories.

The design and application of full-scale carbon adsorption systems is a mature science. Designs are often based on theoretical predictions; however, a significant portion of design comes from "rule-of-thumb" factors and past operating experience. During adsorption, solvent-laden air (SLA) passes through the carbon bed at superficial velocities in the range of 0.15 to 0.50 meters per second (30 to 100 feet per minute). Bed depths range from 50 to 125 centimeters (20 to 50 inches). Usually, the inlet SLA temperature is less than 38°C (100°F) and the relative humidity is less than 50 percent. For regeneration of the carbon bed, low pressure steam is used to heat the bed and displace the adsorbed solvents. After steam regeneration, most designs provide for a cooling/drying period before the carbon bed is placed back in service.

DESIGN PARAMETERS

Six full-scale carbon adsorption facilities were tested for measurement of VOC reduction performance. Two carbon adsorption systems were tested in each of the following surface coating industries: rubberized fabric (Plants 1 and 5), magnetic tape (Plants 2 and 3), and flexible packaging (Plants 4 and 6). The tested plants represent a wide range of designs. For example, the adsorption systems at the rubberized fabric and flexible packaging plants feature horizontal carbon beds, although SLA flow direction through the beds differs (downward for the rubberized fabric plants and upward for the flexible packaging plants). Conversely, the magnetic tape plants feature adsorption systems with annular carbon beds although, again, SLA flow direction through the bed differs (inward for Plant 2 and outward for Plant 3). The number of carbon beds also varies considerably, depending on system size. The smallest system at Plant 1 (SLA capacity of 5.3 Nm^3/sec) has two beds, while the largest facility at Plant 6 (37.8 Nm^3/sec) features six beds.

The relative SLA flow rates, as compared to the bed carbon capacity, average approximately 0.0015 Nm^3/sec-kg carbon (1.5 scfm/lb carbon) for the six tested systems. Four of the plants have systems with relative SLA flow rates closely approximating this average value, but the designs for the adsorption systems at Plants 2 and 6 deviate significantly from the mean. The Plant 6 system design features a relatively conservative 0.00069 Nm^3/sec-kg carbon (0.65 scfm/lb carbon), whereas the Plant 2 design is characterized by a relatively high 0.0026 Nm^3/sec-kg (2.5 scfm/lb). Also, the horizontal bed systems generally feature average design superficial bed velocities of 0.45 m/sec (89 ft/min), while the thin-bed designs of the annular bed systems feature lower velocities, nominally 0.33 m/sec (65 ft/min).

Design solvent types vary considerably, although toluene is a major solvent at five of the six plants. The lightest liquid molar volume solvent formulations are used at the magnetic tape plants and the heaviest solvents are used at the flexible packaging plants. The six designs are characterized by significant differences in inlet solvent loadings, with inlet concentrations ranging from less than 1,000 ppmv to over 4,000 ppmv. On a carbon basis, design solvent loadings vary over an order of magnitude, from 0.0066 to 0.097 kg solvent/kg carbon (0.0066 to 0.097 lb solvent/lb carbon).

Cost data were also developed for each of the tested facilities. In 1983 dollars, the total capital costs of the activated carbon systems range from $267,000 (Plant 5) to $2,685,000 (Plant 6). The capital cost normalized to the SLA flow rate ranges from \$51,000 to \$173,000 per Nm^3 (\$24 to \$82 per scfm). The normalized annual costs range from 0.19 to 0.66 \$/kg (0.09 to 0.30 \$/lb) of recovered solvent.

TEST RESULTS

The carbon adsorption systems were tested using EPA and ASTM methods. Inlet and outlet VOC concentrations were measured semicontinuously with flame ionization detector (FID) total hydrocarbon (THC) instrumentation as described in EPA Method 25A. Volumetric flow rates were measured according to EPA Methods 1 and 2. All test results were verified by EPA-specified quality assurance/quality control procedures. Other process information, including steam rate, steam temperature, SLA temperature, and carbon weight, was determined from process instrumentation or design specifications.

Performance parameters for the six tested carbon adsorption systems are compared in Table 2-1. All six plants were originally tested in early 1982. During these tests, data were taken to characterize the VOC removal efficiency of the carbon bed systems and to characterize the condition of the carbon. No data were obtained on fugitive emissions. Therefore, the VOC reductions in Table 2-1 represent only the adsorber efficiencies. Four of the six plants were retested using the same methods approximately 18 to 22 months later. A comparison of the changes in performance was made in an attempt to define the effects of long-term carbon degradation. In general, the data in Table 2-1 indicate significant differences in performance from plant to plant and from test period to test period. However, these differences were not always attributable to carbon degradation.

The inlet VOC measurements for the six tested systems varied between plants and between test periods. Average inlet solvent concentrations ranged from nominally 1,000 ppmv to 3,000 ppmv. These solvent loadings correspond to approximately 5 to 20 percent of the lower explosive limits (LELs) for these

TABLE 2-1. COMPARISON OF TEST RESULTS -- PLANTS 1-6

Industry	Rubberized Fabric			Magnetic Tape			Flexible Packaging			
PLANT	1	5		2		3	4		6	
	Original Test	Original Test	Repeat Test	Original Test	Repeat Test	Original Test	Original Test	Repeat Test	Original Test	Repeat Test
Solvent type	MEK	toluene	toluene	THF/ toluene[a]	THF/ toluene[a]	THF/toluene/ MEK/MIBK/cy- clohexanone	hexane	hexane	toluene/ IPAC	toluene/ IPAC
Adsorption mode length, min.	95[b]	150	200	64	64	47	120	90	470[b]	560[b]
SLA flow rate, Nm^3/sec (scfm)	5.4 (11,400)	4.3 (9,100)	3.7 (7,800)	4.6 (9,800)	4.5 (9,500)	9.4[c] (19,800)	8.3 (17,700)	10.7 (22,600)	15.8[d] (33,400)	16.0[d] (33,900)
Inlet solvent concentration, ppmv	2,190	1,940	896	1,470	1,140	3,220	1,260[e]	940[e]	904	847
Adsorber efficiency, % %	84.9	97.6	80.5	99.7	95.2	94.7	99.0[e]	46.7[e,f]	97.5	97.9
Desorption mode length, min	55	50	40	32	32	35	25	25	30	30
Steam/recovered solvent, kg/kg (lb/lb)	20 (20)	8.2 (8.2)	15 (15)	5.2 (5.2)	6.5 (6.5)	6.0 (6.0)	4.6 (4.6)	11 (11)	1.0 (1.0)	0.8 (0.8)
Carbon age, years	0.4	5.0	6.5	2.0	3.8	0.4	3.0	4.5	0.2	1.6

MEK = methyl ethyl ketone
THF = tetrahydrofuran
MIBK = methyl isobutyl ketone
IPAC = isopropyl acetate

[a] Original THF/toluene percentages were 50/50; repeat test percentages were 75/25.

[b] Cycle timing controlled by exhaust gas (breakthrough) hydrocarbon analyzer.

[c] Flow rate measured when 4 of the 6 beds were in service (2 beds were on permanent standby).

[d] Process Train 1 conditions (total system capacity was twice that of Process Train 1).

[e] Measurements made at common inlet/common outlet.

[f] Removal efficiency is low due to steam valve leakage (99 percent efficiency was measured after repair of the valves).

compounds. Average adsorption times per bed for the six facilities showed significant variation, ranging from 64 to 560 minutes. Adsorption temperatures were generally less than 38°C (100°F) except for Plant 5. Steaming (desorption) periods ranged from 25 to 55 minutes, with the mean equal to approximately 30 minutes. Steam/recovered solvent ratios varied considerably, ranging from less than 1.0 kg/kg (1.0 lb/lb) at Plant 6 to 20 kg/kg (20 lb/lb) at Plant 1. Steam temperature ranged from 110°C to 150°C (230°F to 300°F).

The average VOC control efficiency data presented in Table 2-1 indicate that, with the exception of the Plant 1 system, all tested adsorption systems were capable of achieving efficiencies of 95 percent or greater. (Mechanical problems at Plants 4 and 5 caused considerable decreases in the VOC control performance during the repeat testing.) Average removal efficiencies exceeding 99 percent were measured for two of the systems during the original testing.

The Plant 2 system showed VOC control performance degradation from 99+ percent (original testing) to 92 percent (repeat testing). Several operating factors may have contributed to this reduction in performance, including solvent formulation changes and changes in adsorption and desorption temperatures. However, these changes would not be expected to be the primary causes for the significant performance decrease measured. Rather, decreasing activity of the carbon appeared to be the primary cause. The deactivation of the carbon at Plant 2 was confirmed when the four-year-old carbon was replaced after the repeat test period, with subsequent plant measurements indicating VOC removal efficiencies exceeding 98 percent. These results suggest a useful carbon life for the Plant 2 system of approximately four years.

Plant 4 experienced significant mechanical malfunctions during the repeat test period resulting in a very low overall VOC reduction performance. However, the low level of baseline emissions (i.e., the VOC emissions excluding excursions due to the mechanical valve malfunctions) indicated that the system was experiencing VOC removal performance similar to that of the original test period. This was verified by VOC analyses performed by the plant after the faulty valves were replaced (after the repeat test period), indicating VOC removal levels similar to those measured during the original testing, i.e., 99 percent. With a carbon age of 4.5 years during the repeat test, the useful carbon life at Plant 4 was estimated to be relatively long.

For Plant 5, the degradation in VOC control efficiency was primarily due to mechanical problems, in particular, a leaking steam valve and channeling in Bed B (these were confirmed and repaired during a system shutdown several weeks after the repeat testing was performed). Variations in cycle timing, higher operating temperatures, lower inlet solvent concentrations, and increased carbon age appeared to account for a smaller portion of the performance decrease. The operating problems and other process variations prevent the accurate comparison of the data sets. However, one major result is apparent, i.e., that the useful carbon service life for the Plant 5 system is at least five years, based upon VOC removal levels of 98 percent measured during the original test period.

Plant 6 VOC control efficiencies were similar during the original and repeat test periods, averaging almost 98 percent. Service time of the bed carbon was relatively short (0.2 to 1.6 years) relative to those of the other tested systems (2.0 to 6.5 years), and operating conditions were much more similar during the two test periods than for the other tested systems. Also, conservative design principles are incorporated into the Plant 6 carbon adsorption system. Because Plant 6 has a conservative design and has exhibited a lack of performance degradation between the two test periods, the useful life of the carbon is projected to be relatively long, perhaps in excess of five years.

CONCLUSIONS

As mentioned in Section 1, the objectives of the study were first to determine the effects of carbon age on system performance and second to measure the performance of a well-operated, fixed-bed carbon adsorption unit. From the test results, the following conclusions can be drawn.

The useful carbon life for a fixed-bed, steam-regenerated system will vary from plant to plant. Four of the six plants tested in this study had carbon lives ranging from four to six years or greater. The other plants had useful lives as short as only a few months. No methods were identified which could be used to predict the length of carbon life.

Of the fixed-bed carbon adsorption systems tested, all but one were capable of 95% VOC reduction across the system. Some systems operated routinely at levels greater than 99% VOC reduction. These systems recovered a variety of solvents including toluene, THF, MEK, hexane, isopropryl acetate, MIBK, and cyclohexanone. The single system which operated below the 95 percent level was poorly maintained and at one time experienced severe corrosion problems. Soon after the testing was completed for this study, the entire system was scrapped and replaced with a fluidized-bed carbon adsorption system. Additional testing at a later date at the original test sites showed in some cases reduced VOC removal performance. However, these reductions in performance generally could be related to malfunctions in equipment (i.e. faulty valves, bed switching problems) rather than carbon age. When the malfunctions were corrected, previous performance levels were measured.

Finally, a computer model developed by Dr. Kenneth Wilde was used to predict the VOC reduction performance of fixed-bed, steam-regenerated systems. Although, the model could provide adequate data to predict relative performance levels, accurate prediction of the absolute VOC removal performance would require refinement of the model which is beyond the scope of this study.

RECOMMENDATIONS

There are no established procedures to accurately predict useful carbon life. Also, currently used test methods, such as the CCl_4 activity test, do not appear to provide the data needed to measure adsorption capacity for used (degraded) carbons. Therefore, it is recommended that new test methods be developed to measure adsorption capacity (and other carbon properties such as retentivity and fouling) of used carbons, and that procedures be developed to use that data for estimating carbon life. These test methods will probably be performed in a controlled environment, such as a bench-scale or pilot-plant facility, to eliminate possible interferences, such as equipment malfunction or changes in operating conditions, which are often encountered during testing of full-scale units. Also, the carbon life tests may include gas-phase testing of the SLA stream to determine the presence of possible contaminants which can foul the carbon bed.

As part of the testing, an investigation of the mechanisms for carbon degradation is needed. Most degradation is believed to be caused by one or more of the following mechanisms: (1) adsorption or physical blockage of the micropore structure by contaminants, (2) obstruction of adsorption sites by by-products of organic polymerizations or reactions on the carbon surface, or (3) chemical reaction involving the carbon surface leading to a reduction in the availability of active sites. Information in the literature on these mechanisms is limited.

The data developed from the above investigations can be used to further develop the Wilde Model for prediction of VOC reduction performance of a fixed-bed carbon adsorption system. The data which is gathered should attempt to represent actual carbon-bed operations rather than be indirect measurements of system performance such as ccl_4 activity and retentivity. In addition, special emphasis should be placed on the regeneration aspects of the fixed-bed system. Limited data have been developed on this aspect of the process. Accurate characterization of the regeneration process is as important as accurate characterization of the adsorption cycle.

Also, methods to extend useful carbon life should be investigated. In some applications, carbon life is acceptable; however, in situations where carbon life is very short (i.e., less than one year), the extension of acceptable carbon performance through installation of a carbon bed protection device can be cost effective. Selection of an appropriate carbon bed protection device will be determined in large part by the mechanism by which the bed becomes deactivated. Current methods for extending carbon life may include pretreatment of the SLA stream with a fabric filter, a sacrificial guard bed, or a wet scrubber.

A final recommendation concerns monitoring breakthrough of carbon beds. For multicomponent systems, the initial carbon bed breakthrough will typically consist of only one component of the multicomponent mixture. If the hydrocarbon monitor is not selected or operated to identify that particular component, the breakthrough trend may be improperly measured, resulting in an inordinately low recovery of that particular component. Also, if direct-fired gas ovens are used in the coating operation, the adsorber monitoring system should be designed to ignore methane as a breakthrough component. In general, direct-fired ovens will exhaust unburned methane, which is detected as a hydrocarbon by most total hydrocarbon (THC) analyzers. This situation can lead to erroneous THC measurements and possible premature indication of carbon bed breakthrough.

SECTION 3

CARBON ADSORPTION THEORY

The adsorption process refers to the attraction of certain molecules (adsorbate) from a fluid phase onto the surface of an adjoining solid (adsorbent) phase. For gas-phase activated carbon adsorption, the two phases are the organic or solvent-laden air (gas phase) and the activated carbon (solid phase).

The gas-phase carbon adsorption process has been studied extensively in academia and industry. This section provides a brief review of some of the important theoretical findings and their relationship to the operation of fixed-bed activated carbon systems.

ACTIVATED CARBON

A wide variety of adsorbents is available, depending upon their base material and their intended use. Adsorbents can be categorized as follows: (1) chemically reactive adsorbents, (2) polar adsorbents, (3) nonpolar adsorbents, and (4) molecular sieves. Activated carbon is a prime example of a nonpolar adsorbent and is the only adsorbent investigated in this study.

Activated carbons are manufactured from a number of carbonaceous materials, including coal, coke, petroleum products, wood, peat and coconut shells. To a large extent, the specific application and the characteristics of the final active carbon product are determined by the base material.

Activated carbons are produced by thermal decomposition of the carbonaceous base material followed by controlled oxidation (activation) using steam, carbon dioxide and/or air. The thermal decomposition process releases volatile matter within the base material, leaving a porous structure. The oxidation process further refines the pore structure and increases the pore size and volume. If the oxidation process is continued too far, the active or micropore structures will burn out and form larger but inactive pore structure. Therefore, the oxidation process significantly determines the activity of the final carbon product.

As mentioned above, the type of pore structure is dependent upon the base material and the activation conditions. The pores are typically classified as macropores and micropores. The macropores have diameters of at least 30 Angstroms (Å) and are generally greater than 1,000 Å in diameter. The micropores are less than 30 Å in diameter, with most having diameters of 10 to 20 Å. Typical pore size distributions for selected carbons are shown in Figure 3-1.

Physical properties of several activated carbons are presented in Table 3-1. As shown, industrial grade activated carbons can be obtained in granular, powder or pellet form. Size ranges are from 4 x 6 mesh (coarse) to 12 x 20 mesh (fine) with typical bulk densities of 0.40 to 0.55 g/cm^3 (25 to 35 lb/ft^3). Also, the activated carbon pore structure results in the availability of a large surface area (up to 1,600 m^2/g) for adsorption.

Although not tabulated, carbon hardness and ash content are also important physical properties. The hardness is particularly significant where thermal regeneration is used, due to the associated thermal stresses (in addition to packing and fluid dynamic stresses). Nearly all carbons contain ash, or other noncarbonaceous material, such as sulfur, which influences or inhibits the adsorption mechanism. The ash may catalyze reactions involving the organic adsorbate resulting in the formation of undesirable reaction products on the carbon. Petroleum and coal-based carbons are particularly high in ash content, while wood and shell carbons are not.

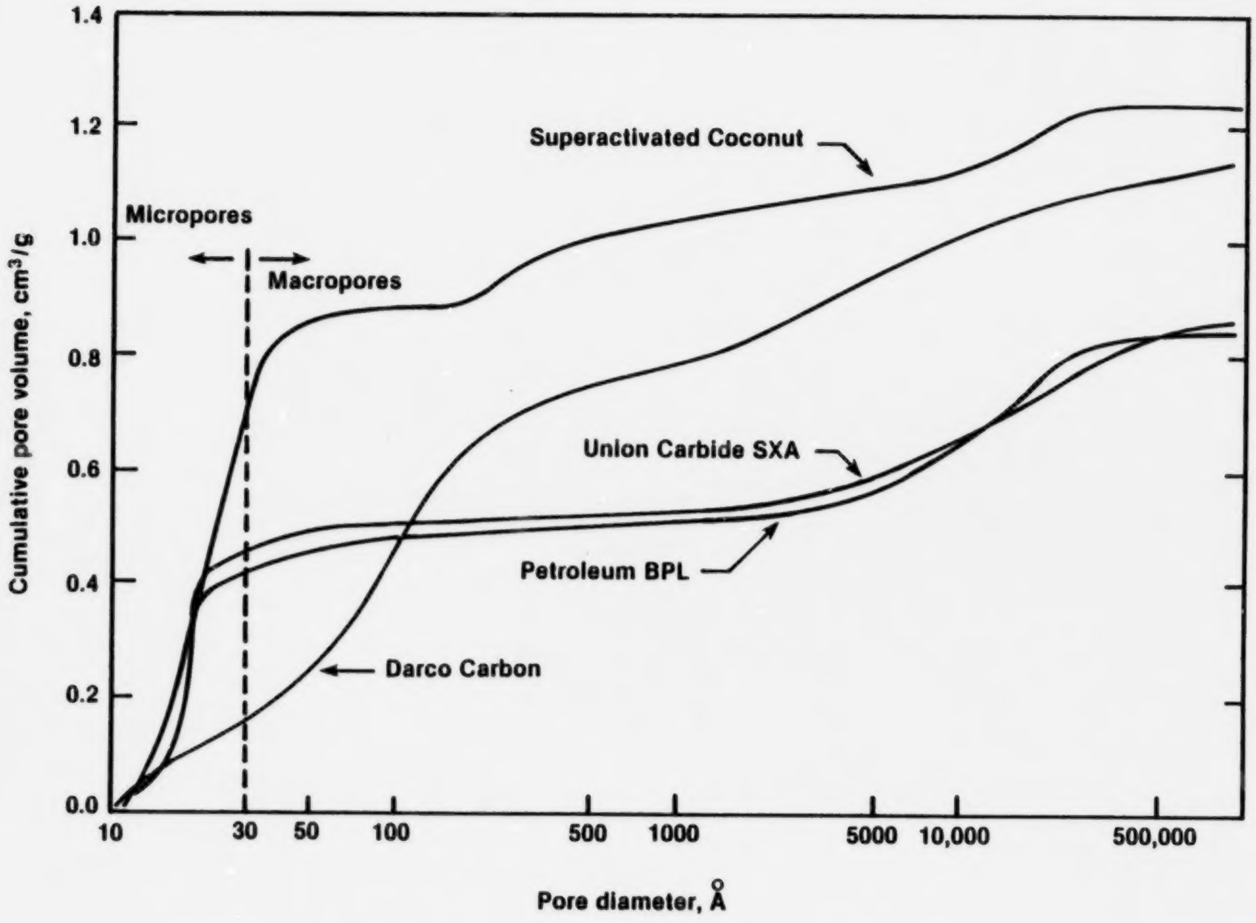


Figure 3-1. Pore size distribution curves for activated carbon.

TABLE 3-1. PHYSICAL PROPERTIES OF ACTIVATED CARBONS

Material and Typical Use	Shape of Particles	Size Range, U.S. Standard Mesh	Internal Porosity %	Bulk Dry Density, g/cm^3	Avg. Pore Diam., Angstroms	Surface Area, m^2/g	Adsorptive Capacity, g/g dry solid	Trade Designation
Shell-based	G	Various	50-60	0.43-0.54	20	800-1100	0.45	Cochranex FCB;Pittsburgh PCB
Uses (for all carbons):	G	Various	50-80	0.40-0.55	20-30	1000-1600	0.5-0.95	Picatif T.A.,T.E.
water treatment, gas	G, P	Various	60-65	0.43-0.56	18-19	1200-1500	∼0.4	Acticarbone NC,WNC
purification, solvent	G	Various	∼50	0.43-0.51	20	800-1100	0.45	Barnebey-Cheney AC,KE,VG,PC,PL
recovery and decolorizing	G	4X6,8X30	∼50	0.52-0.55	20	800-900	. . . . .	Girdler 32E (Fe-impregnated), 32W (Cu-Cr-impregnated)
	P	. . . . .	60-80	0.32-0.35	∼30	1200	. . . . .	Barnebey-Cheney YF,JF,JU (high capacity)
Wood-based.	C,P	1/8,1/5 in.	70-75	0.19-0.45	22-24	750-1450	. . . . .	Acticarbone AC, etc.; Anticromos
	P	Various	30-50	0.14-0.55	. . . . .	600-1200	. . . . .	Darco KB,G60;Nuchar Aqua,Nuchar WA, B-100, C-115, CEE,C-190, C,C-1000
	G	5X7	. . . . .	0.39	5-10	1400	. . . . .	Supersorbon W
	P	Various	. . . . .	0.33-0.43	8-30	1000-1500	. . . . .	Carboraffin (various grades)
	P	Various	. . . . .	0.43-0.47	3-10	790-900	. . . . .	Brilonit (various grades)
	G	10X30,etc.	60	0.32	20-40	600-1000	. . . . .	Cochranex FCN-1,FCN-2,FCA,FCC
	G	Various	40-50	0.24-0.32	20-100	800-1200	40-70%	Picatif C.O.
	P	100-300	40-60	0.43-0.53	. . . . .	600-1200	80-130%(I_2)	Picatif CM
Peat-based.	C,G,P	Various	∼55	0.24-0.51	30-40	500-1600	. . . . .	Norit (various grades)
	G	5x7	. . . . .	0.32-0.39	5-20	1300-1400	. . . . .	Supersorbon (various grades)
	P	<200	. . . . .	0.45-0.50	. . . . .	700-900	. . . . .	Acticarbone AM, AH
Coal-based.	G	Various	65-75	0.32-0.49	20-38	500-1200	0.4	Darco Granular;Permutit Carbo-Dur
	G	12X40,etc.	60	0.49	60-65	800-1000	. . . . .	Cochranex FCP-1,FCP-2,FCW-V
	G, P	Various	56-67	0.40-0.49	20	1000-1400	. . . . .	Pittsburgh BPL,CAL,SGL,etc.(RB,RC,BL)
	G	. . . . .	80	0.45	22	110	50	Barnebey-Cheney MN
	G	Various	. . . . .	0.43-0.59	. . . . .	850-1350	30-60%	Acticarbone LM;Nuchar WV-W,WV-L, WV-G,WV-H
	G	5X7	. . . . .	0.32-0.39	5-15	1300-1500	. . . . .	Contarbon (various grades)
	P	. . . . .	. . . . .	0.40-0.49	. . . . .	600-700	. . . . .	Darco BG,DC,S-51;Hydrodarco B
Petroleum-based	C,P	Various	65-85	0.49	18-22	800-1100	. . . . .	Columbia (various grades)

G = granular, P = powder, C = cylindrical pellets

Source: Perry and Chilton, Chemical Engineers Handbook, (5th Edition).

GAS-PHASE ADSORPTION

The adsorption of a gas on a solid surface can occur in one of two ways. In the first case, relatively weak forces physically attract the gas molecules to the surface of the adsorbent. The chemical nature of the molecule remains unchanged in this adsorption, which is known as physical, or van der Waals, adsorption. In the second case, the gas molecule is chemically bonded to the adsorbent through electron exchange or sharing. This bond is much stronger and is known as chemisorption (or chemical adsorption) (3). With activated carbon, the only adsorption mechanism is physical adsorption; therefore, the discussions in the next sections will pertain only to physical adsorption theories.

Concept of Physical Adsorption

In physical adsorption, a gas molecule is attracted to the active carbon surface and bound to the surface for a certain period of time. This time period is known as the lifetime or time of adsorption and is a statistical quantity. It depends on factors which determine the strength of the adsorptive bond, e.g., the carbon properties, the gas molecule properties, the temperature of the adsorbing surface, and the kinetic energy of the molecule. In physical adsorptions of gases and vapors on active carbon at room temperature, the time of adsorption is in the range of 10^{-12} to 10^{-2} seconds (3). With such short lifetimes, equilibrium is reached very rapidly and, for most practical cases, can be assumed to be reached instantaneously. The adsorption equilibrium is a dynamic situation because the number of molecules leaving the surface per unit time is equal to the number of newly adsorbed molecules.

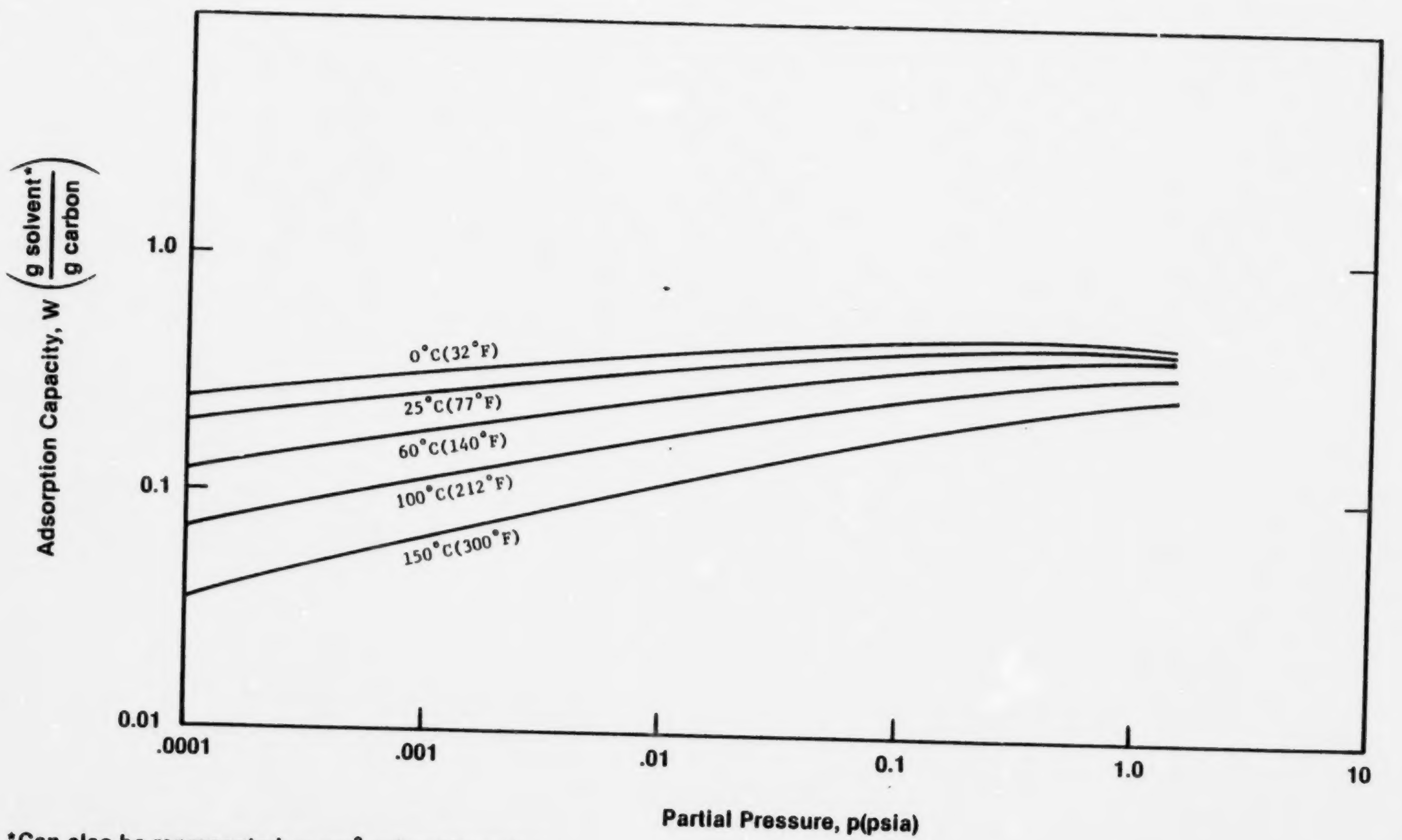
The micropore structure, which comprises as much as 45 percent of the carbon volume, controls the overall adsorption mechanism. Within the micropores, an imbalance of forces (van der Waals forces) exists at the pore wall surface. To balance these forces, organic molecules are attracted and physically held to the surface. As mentioned previously, the chemical nature of the molecule remains unchanged. The macropore structure does not participate in the adsorption process except to provide pathways to the micropores.

Adsorption Isotherm

An important concept in understanding and designing an activated carbon bed system is the adsorption isotherm. The adsorption isotherm describes the adsorptive capacity of a particular carbon at a constant temperature and varying equilibrium pressures of the adsorbate in the bulk gas phase. Groups of isotherms are often developed for individual adsorbent-adsorbate pairs, as shown by the typical set of isotherms in Figure 3-2.

Several theories have been developed to describe the adsorption equilibrium and to predict the adsorption isotherm. During the first World War, two prominent theories of adsorption were developed: the potential theory of Polanyi and the kinetic theory of Langmuir. The kinetic theory resulted in the first theoretically-developed equation of the adsorption isotherm. However, the potential theory of adsorption and the Dubinin equation, which is based on it, proved to be more useful than all other theories. Therefore, the following discussions will be limited to the potential theory.

The potential theory of adsorption is based upon the assumption that there exist fields of attraction of varying strength (adsorption potentials) near the surface of the carbon. The field of highest potential is at the carbon surface, while at some point away from the surface, the potential is reduced to zero. The adsorption potential, ε, is assumed to exist in equipotential planes as shown in Figure 3-3a (3). The volume between the equipotential plane and the adsorbing surface is the adsorption capacity, W. Therefore, at the point of zero potential, the volume for adsorption, W_0, is maximized.



*Can also be represented as cm^3 solvent/g carbon

Figure 3-2. Typical adsorption isotherms.
Source: Calgon Corporation, Pittsburgh, PA

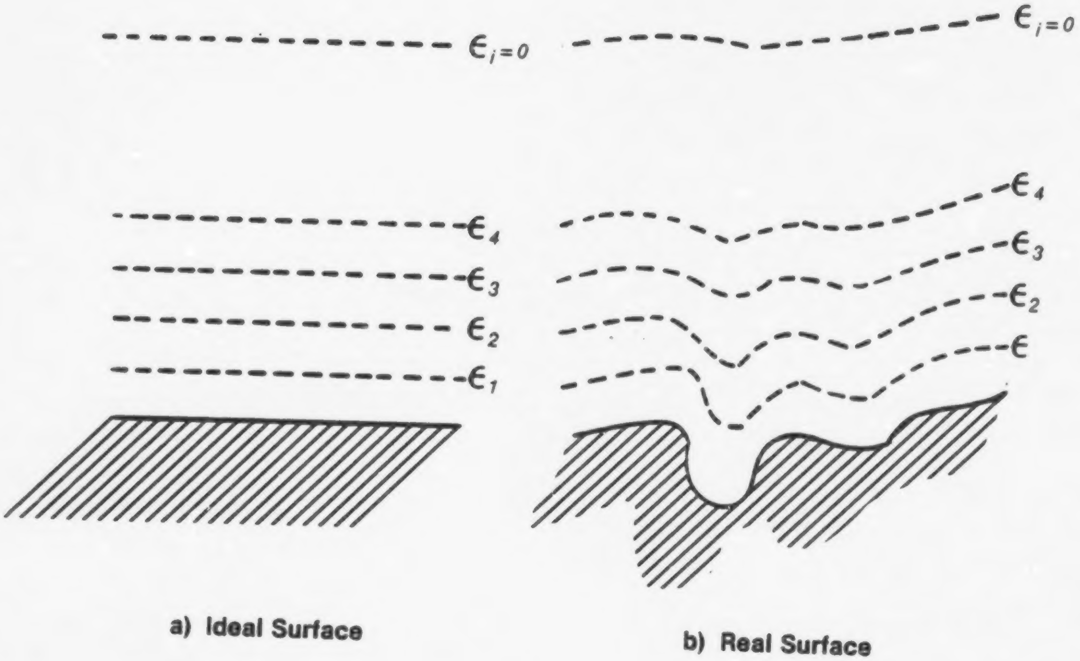

$\epsilon_{i=0}$
ϵ_4
ϵ_3
ϵ_2
ϵ_1
$\epsilon_{i=0}$
ϵ_4
ϵ_3
ϵ_2
ϵ
a) Ideal Surface
b) Real Surface

Figure 3-3. Schematic representation of the potential fields at the surface of solid adsorbents.

In real situations, the surface of the adsorbent is not flat (as shown in Figure 3-3b) and the relationship between the equipotential surface and the adsorptive capacity is much more complex. However, there still exists a unique function such that for each value of the adsorption potential, ε, there corresponds a definite volume, W, of the adsorption space. The functional relationship between ε and W is expressed for every adsorbent by the characteristic curve. Figure 3-4 shows the characteristic curves for several different vapors on carbon.

The potential theory further assumes that, when the adsorption temperature is well below the critical temperature of the adsorbate, the density of the adsorbed vapors may be considered to be equal to the liquid density of the adsorbate at the adsorption temperature. Using this assumption, the adsorption potential, ε, represents the work needed to isothermally compress the vapors from their equilibrium pressure (p) in the gaseous phase to the saturated vapor pressure (ps) at a given temperature of adsorption. Therefore, the adsorption potential can be expressed as follows:

$$\varepsilon = RT \ln ps/p \tag{3-1}$$

where R is the ideal gas law constant and T is the temperature of adsorption.

The use of the potential theory was significantly enhanced when Dubinin was able to relate the theory to an analytical equation for the adsorption isotherm. Dubinin first recognized that the characteristic curves of different vapors on a single carbon (Figure 3-4) are affine, i.e., related. This means that if the adsorption potential, ε^*, corresponding to a chosen adsorptive capacity, W, for one vapor is multiplied by a certain constant, the adsorption potential, ε, corresponding to the same value of W is obtained for another vapor. Therefore, the following relationship can be formulated:

$$\varepsilon = \varepsilon^* \beta \tag{3-2}$$

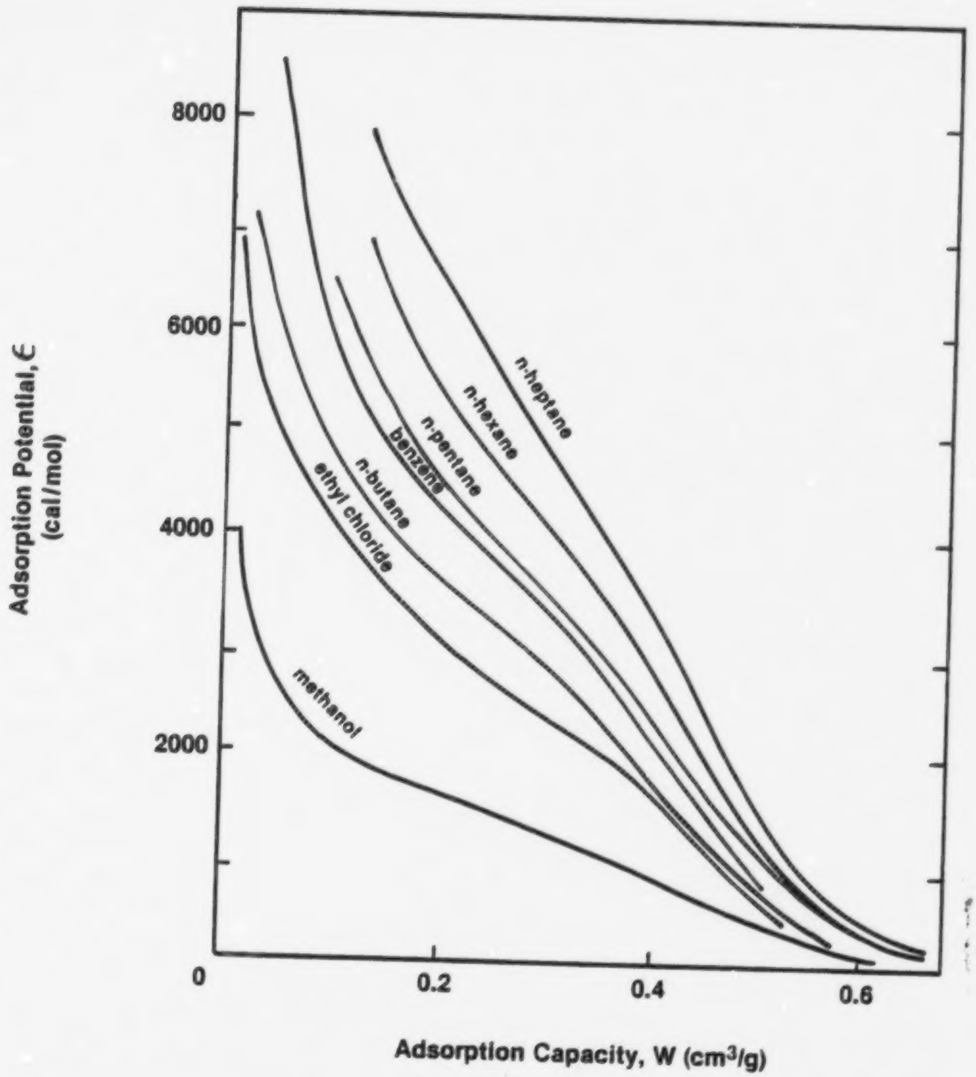


Figure 3-4. Affinity of characteristic curves of different vapors on an active carbon.

where β is the affinity coefficient. Table 3-2 lists affinity coefficients for several vapors on a single carbon with benzene as the reference compound (i.e., $\beta = 1$).

In further study of characteristic curves of vapors on active carbon, Dubinin and Radushkevich found that for most adsorbent-adsorbate pairs, the shape of the curve is very similar to the positive branch of the Gaussian distribution curve. Therefore, they chose to represent the characteristic curves analytically by an equation of the form of the Gaussian distribution:

$$W = W_o \exp\left[-K(\varepsilon^*)^2\right] \qquad (3\text{-}3)$$

where W_o is the limiting adsorptive capacity and K is a constant related to the carbon pore structure. For most active carbons, W_o is very approximately equal to the total volume of the micropores. Combining and expanding equations 3-2 and 3-3 results in the classic Dubinin-Radushkevich equation for the adsorption isotherm:

$$\ln W = \ln W_o - K\left(\frac{\varepsilon}{\beta}\right)^2 \qquad (3\text{-}4)$$

where:

$$\varepsilon = RT \ln ps/p \qquad (3\text{-}5)$$

This equation is often used in carbon adsorption design and applications to predict the adsorption isotherms of various adosrbent-adsorbate pairs. Current refinements of the equation center on predicting the affinity coefficient, which has been related to the molecular volume, molecular parachor and electronic polarization of the adsorbate (4,5).

Another important isotherm considered in the design of activated carbon bed systems is that for water vapor. The adsorption isotherm for water vapor on active carbon is different than most organic vapor isotherms, as shown in Figure 3-5 (6). As can be seen, the amount of water vapor adsorbed increases dramatically at relative humidities greater than 50 percent. Also, the water vapor isotherm has a unique behavior in that the shape and location of both

TABLE 3-2. AFFINITY COEFFICIENT β FOR SOME VAPORS ON ACTIVE CARBON[a]

Benzene[a]	1.00
Cyclohexane	1.04
Toluene	1.25
Propane	0.78
n-Butane	0.90
n-Pentane	1.12
n-Hexane	1.35
n-Heptane	1.59
Methanol	0.40
Ethanol	0.61
Methyl chloride	0.56
Methyl bromide	0.57
Chloroform	0.86
Tetrachloromethane	1.05
Dichloromethane	0.66
Ethyl chloride	0.76
Tetrafluoroethylene	0.59
Hexafluoropropylene	0.76
Chloropicrin	1.28
Ethyl ether	1.09
Acetone	0.88
Formic acid	0.61
Acetic acid	0.97

[a] Benzene is used as the reference compound.

Source: Smisek, Active Carbon

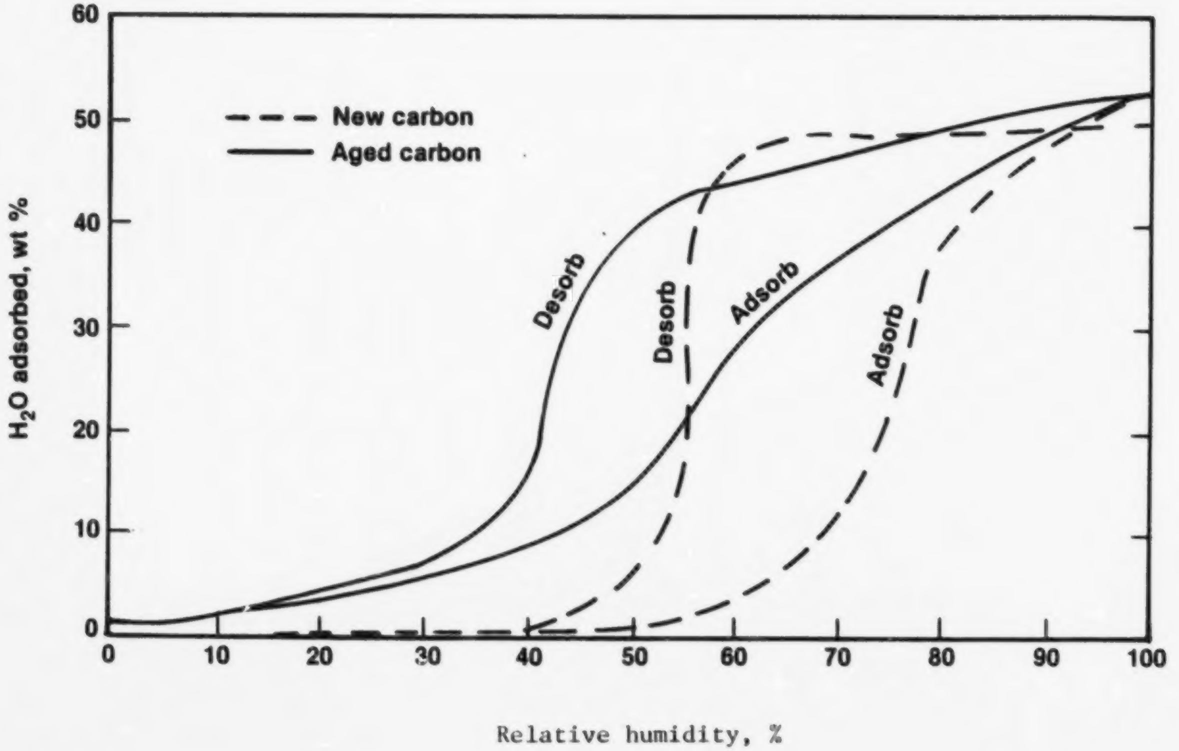


Figure 3-5. Water vapor adsorption isotherm at 25°C on new and aged (oxidized) carbons (coconut shell carbon: 1050 ± 50 m^2/g).

the adsorption and desorption branches change with aging (exposure to oxygen) of the activated carbon. The changes are due to the formation of surface oxide complexes, which influence the surface polarity and greatly increase the number of active sites for adsorption of water vapor.

ADSORPTION OF MIXTURES

While significant work has been done to characterize the adsorption isotherms of single-component gas streams, less work has been done on multicomponent systems. Multicomponent systems are much more complex, and thus prediction of equilibrium is more difficult. In general, the studies on multicomponent systems have attempted to extend the data on pure components or have attempted to use thermodynamic methods. In the 1960's, Myers and Prausnitz presented the theory of ideal adsorbed solutions (IAS) for multicomponent systems (7). This method provided quantitative agreement with experimental data on a wide variety of gas mixtures and for different heterogenous adsorbents. Although other theories have since been presented, a detailed discussion of these theories and the IAS theory is beyond the scope of this report.

ADSORPTION DYNAMICS

Isotherm data provide information on the equilibrium adsorptive capacity of an activated carbon system. However, most industrial applications involve dynamic situations, i.e., a solvent-laden air (SLA) stream passing through a fixed carbon bed. Understanding of both the equilibrium and dynamic characteristics of a carbon bed system is necessary to permit calculation of the contact (or adsorption) time and the amount of carbon required to achieve a certain removal.

Mass Transfer Zone and Breakthrough

The dynamic characteristics of a fixed-bed carbon adsorber can best be described with the concept of a mass transfer zone. As the SLA enters a new or freshly regenerated bed, an adsorbed solvent concentration profile begins to form as shown in curve 1 in Figure 3-6 (1). As more SLA passes through the bed, the profile enlarges (curve 2) until the bulk gas phase reaches equilibrium with the solvent adsorbed on the carbon. At this point (curve 3), the carbon at the influent side of the carbon bed is saturated and will not remove any additional solvent (provided the inlet concentration does not change). As more SLA passes through the bed, the saturated zone moves deeper into the bed, preceded by the concentration gradient (curve 4). The zone of the bed where the concentration gradient is present is referred to as the mass transfer zone (MTZ).

Eventually the MTZ gradient will extend past the effluent end of the carbon bed (curve 5). The start of this process is known as breakthrough. For solvent recovery systems, breakthrough concentrations are often monitored to determine when the beds should be regenerated. This allows full use of the carbon bed capacity for a given VOC removal efficiency.

Factors Affecting the Mass Transfer Zone

The length and rate of movement of the MTZ affect the design and sizing of the carbon bed. Factors which affect the MTZ length and rate of movement include (6):

1) type of adsorbent and adsorbate;

2) particle size of the adsorbent;

3) depth of the adsorbent bed;

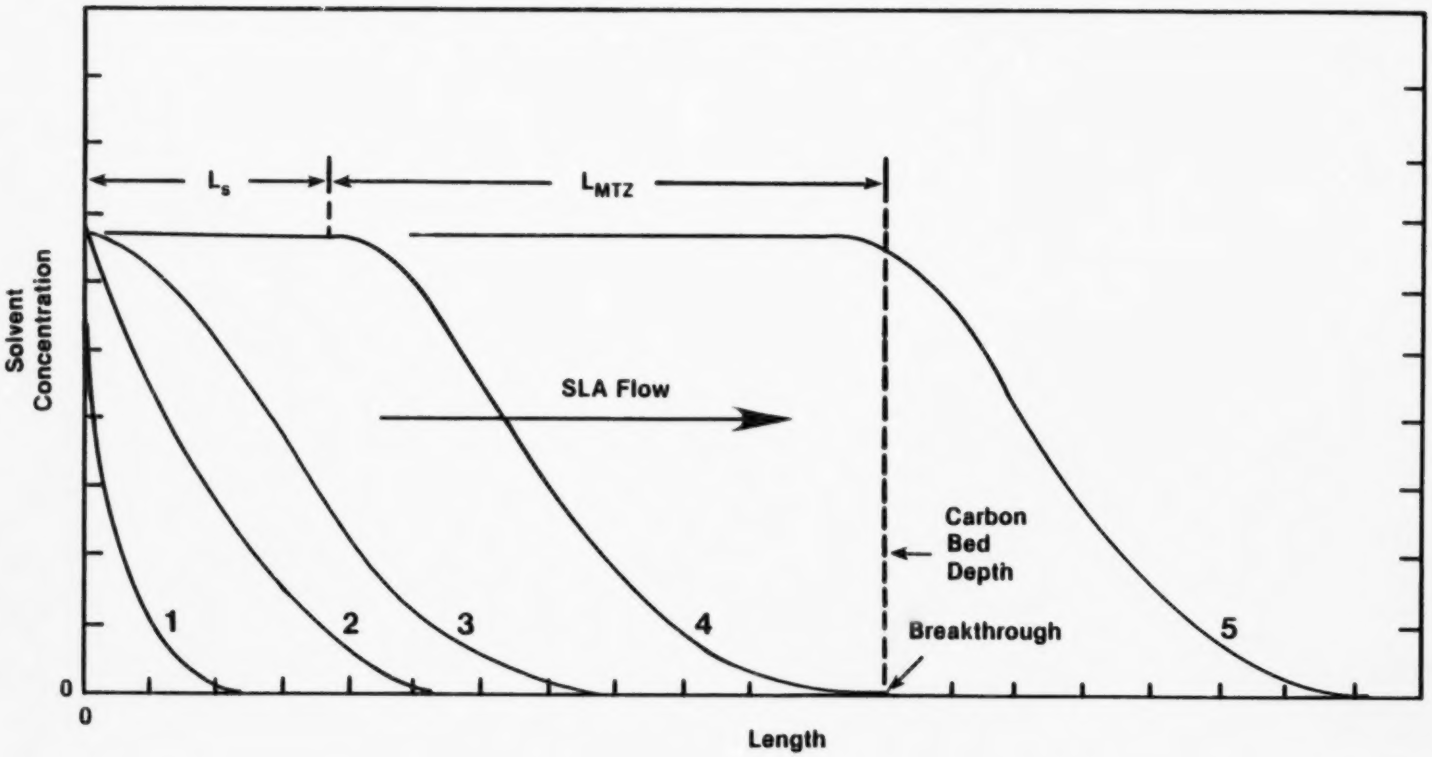


Figure 3-6. Movement of vapor concentration front in carbon bed with increased adsorption time - single solvent.

4) gas velocity;

5) temperature of the gas stream and adsorbent;

6) concentration of the contaminants to be removed;

7) concentration of contaminants, including moisture, not to be removed;

8) system pressure;

9) removal efficiency required; and

10) possible decomposition or polymerization of contaminants on the carbons.

The relationship between MTZ length and gas velocity, particle size, and molecular volume of the adsorbate is shown in Figure 3-7 (1). For any carbon bed system, the length of the MTZ should be less than the bed depth. When deep beds are used, as in solvent recovery applications, the saturated zone is large relative to the MTZ. For typical systems with superficial velocities of approximately 0.5 m/ sec (100 ft/min), the MTZ is on the order of 8 cm (3 inches), while the saturated zone ranges from 40 cm (16 inches) to over 90 cm (36 inches).

Bed depth can also affect the length of the MTZ. As the bed depth increases, the MTZ will tend to lengthen due to diffusion of the adsorbate within the void spaces. However, for most solvent recovery systems, this effect is not significant, since solvent recovery systems are typically designed for the maximum bed depth allowed by pressure drop considerations.

The shape and speed of the MTZ are determined by the diffusion characteristics of the adsorption system. As previously discussed, in a quiescent bed, the mass transfer occurs by diffusion of the adsorbate from the bulk gas phase

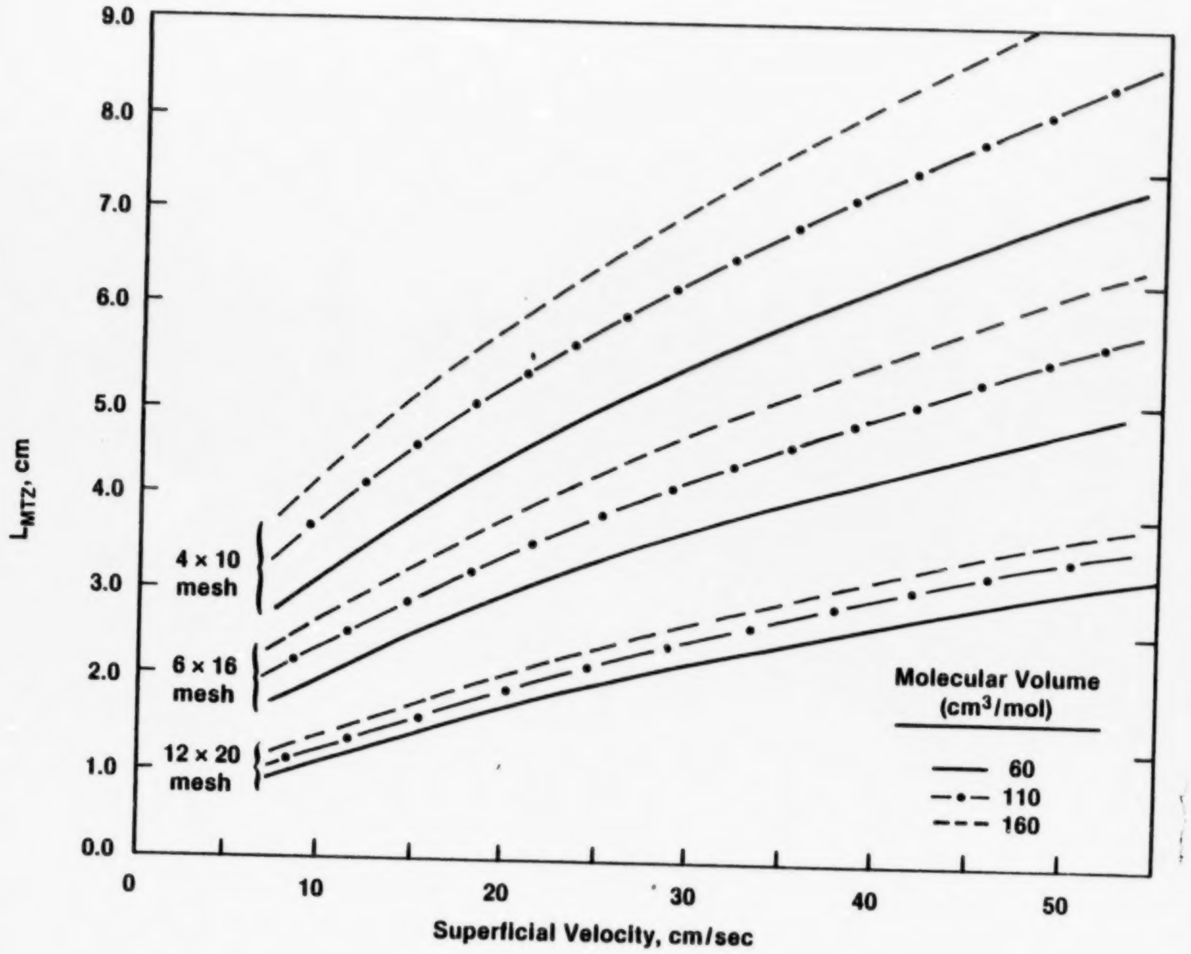


Figure 3-7. Effect of superficial gas velocity on adsorption zone length, LMTZ, for three sizes of carbon.

through the macropores of the carbon to the micropore structure, where it is held by van der Waals forces. In the dynamic situation, the solvent-laden gas phase passes over the carbon particles resulting in a different diffusion rate than for a static situation. The dynamic situation is characterized by the formation of a thin stationary gas film near the particle surface. The transfer of the adsorbate from the bulk gas occurs within this film. From there, adsorption continues into the particle pores by pore diffusion. Because diffusion determines the mass transfer rates, all parameters (e.g., temperature and adsorbate concentration) that affect any of these diffusion steps will also influence the equilibrium conditions within the bed and determine the shape of the MTZ.

Adsorption of materials other than those desired for removal can affect the MTZ size and movement and also greatly affect the capacity of the carbon. Water vapor, carbon dioxide, and any other large molecular weight or high-concentration/low-molecular weight adsorbate will influence the adsorptive capacity for the design adsorbate. Water vapor will influence removals at high relative humidities (i.e., greater than 50 percent), particularly during the adsorption of relatively polar solvents (6). The presence of moisture and other contaminants will tend to increase the rate of movement and length of the MTZ.

Some solvents may decompose, react, or polymerize when they come into contact with activated carbon. Activated carbons often contain trace metals which provide catalytic sites for chemical reaction, especially during relatively hot regeneration periods. Besides possibly creating corrosive materials, the reactions can foul or coat the active surface of the carbon and greatly reduce its adsorptive capacity.

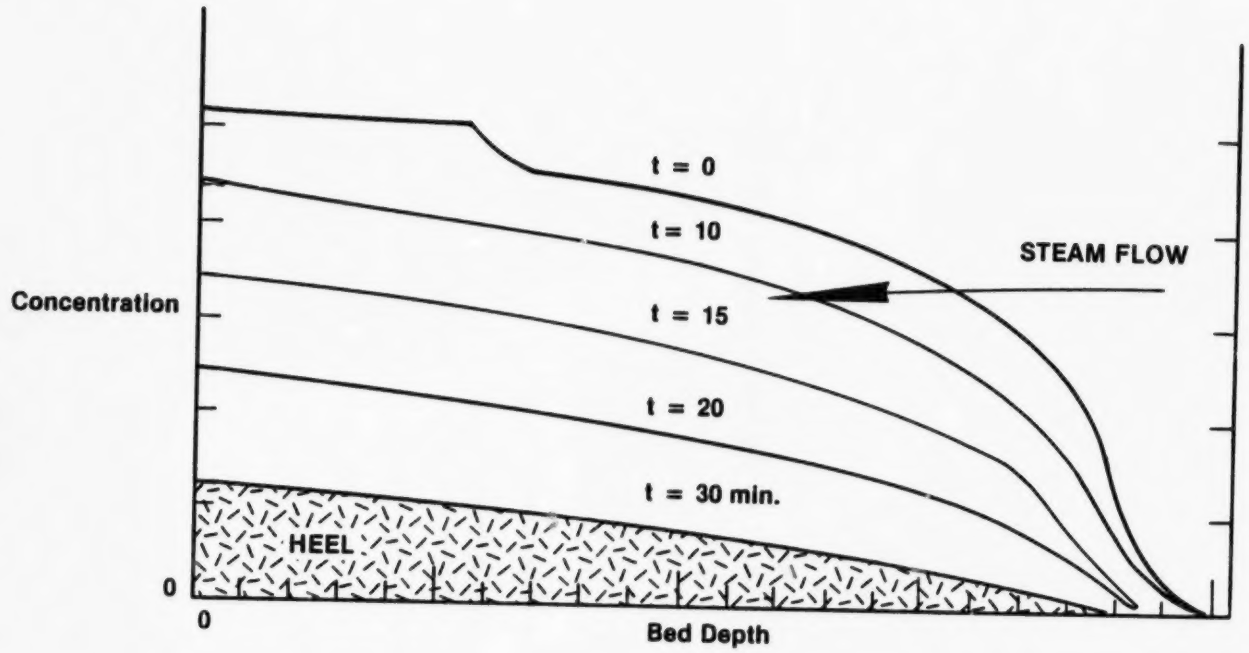


Figure 3-8. Desorption concentration profile in carbon bed with increased desorption time.

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SECTION 4

REVIEW OF SURFACE COATING OPERATION AND APPLICATIONS OF FIXED-BED CARBON ADSORPTION

Surface coating operations include several potential sources of VOC emissions. The level of control of these sources, if any, depends on a number of factors including the physical design of the coating system. Carbon adsorption represents a widely used add-on VOC control technlogy for many surface coating VOC sources. This section reviews surface coating industries and carbon adsorption operations that are applicable for these industries.

SURFACE COATING OPERATIONS

Surface coating refers to the application of a material to a paper, plastic, metal, fabric, or wood substrate to form an intermediate- or end-product with certain desired characteristics. Often the material applied to the substrate is borne or dissolved in an organic solvent. The solvent acts as a "carrier" that is ultimately evaporated from the coated surface.

A typical surface coating operation is shown in Figure 4-1. In this example, a continuous sheet (or web) of the raw substrate is unwound from a feed roll and introduced to a coating station. At the coating station, the liquid coating is applied to the web using any one of several available coating techniques (e.g., roll coater, knife coater, spray coater, dip coater, etc.). The wet coated web is then dried or cured; i.e., the solvents are evaporated from the surface by the application of direct (fired) or indirect (steam) heat. The dried web is wound up on a product take-up roll.

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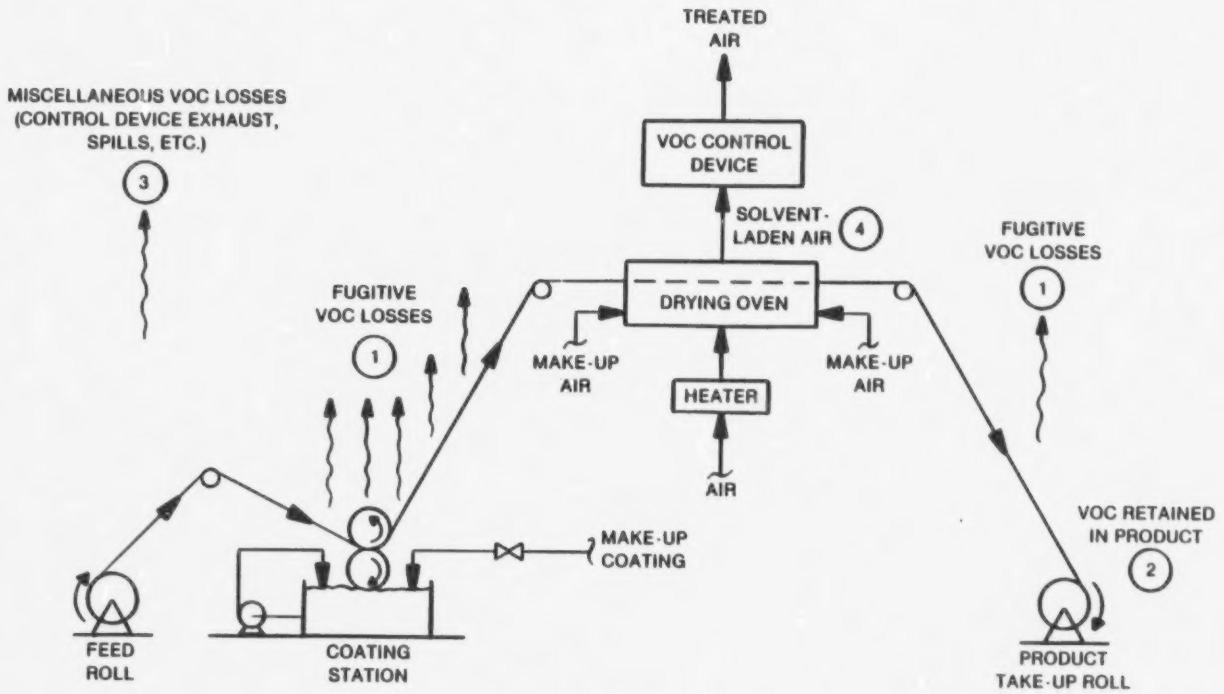
TREATED
AIR
MISCELLANEOUS VOC LOSSES
(CONTROL DEVICE EXHAUST,
SPILLS, ETC.)
③
VOC CONTROL
DEVICE
SOLVENT-
LADEN AIR
④
FUGITIVE
VOC LOSSES
①
FUGITIVE
VOC LOSSES
①
DRYING OVEN
MAKE-UP
AIR
MAKE-UP
AIR
HEATER
AIR
VOC RETAINED
IN PRODUCT
②
MAKE-UP
COATING
FEED
ROLL
COATING
STATION
PRODUCT
TAKE-UP ROLL

Figure 4-1. Typical web coating operation.

The substrate does not necessarily have to be in the form of a continuous web. Other common configurations include individual sheets, e.g., wood or metal; cylindrical shapes, e.g., barrels or cans; and miscellaneous shapes, e.g., metal furniture or automobiles. Major surface coating operations representing various substrate configurations are shown in Table 4-1.

Regardless of the substrate configuration or the final coated product, the basic processing steps and VOC emission sources are similar. The VOC emissions can be categorized as follows and as represented in Figure 4-1:

- Fugitive VOC losses from the coating process (Source 1) -- These emissions occur primarily from the coating station or the wet coated substrate (prior to drying). The VOCs can be uncontrolled, captured and vented to the atmosphere, or captured and routed to a control device. Commonly used capture systems include elevated process hoods and floor-level exhaust hoods. A 100% VOC captive may be obtained with a total enclosure around the coater and flash-off area.

- VOC product losses (Source 2) -- Depending on the substrate and solvent/coating type, a certain amount of the solvent may be retained in the final product. As much as five percent of the solvent used in the process can be contained in the final product (1).

- Miscellaneous VOC losses (Source 3) -- VOC losses may also occur in the control device exhaust stream(s), from liquid solvent spills, as solvent storage fugitive losses, etc.

- Volatilized VOC emissions (Source 4) -- These emissions are generated in the drying process, as heat is applied to the wet coated substrate to volatilize the solvent. They typically represent the majority of the solvent VOC losses from the coating operation.

TABLE 4-1. SURFACE COATING OPERATIONS

- Paper coating
  - publication rotogravure
  - pressure sensitive tapes and labels
  - decorative laminates
  - special paper products

- Metal coating
  - decorated metal
  - coil
  - automobile and truck bodies (paint)
  - beverage and food containers
  - barrels and drums

- Wood coating
  - fiberboard
  - paneling

- Fabric coating
  - rubberized fabric
  - glass fabric

- Miscellaneous
  - magnetic tape
  - coated vinyl

Because the volatilized VOC source category (Source 4) typically represents the bulk of the total emissions and because it provides a relatively concentrated and contained VOC stream, it is generally the source that is selected for control (if any).

VOC control is generally accomplished using solvent recovery or solvent destruction techniques. Solvent destruction is accomplished by thermal or catalytic incineration while carbon adsorption is classified as a recovery technique. The type of VOC control is dependent on several factors including solvent type, solvent concentration, removal efficiency desired, and economic considerations. When applicable, carbon adsorption has an advantage because the solvent is recovered and can be reused. In incineration applications, thermal incineration is more commonly used than catalytic oxidation, due to its: (1) simple and reliable operation, (2) lower maintenance costs, (3) consistent performance throughout the unit life, and (4) applicability to a wide variety of VOCs. Catalytic incineration can, however, be more cost-effective. Subsequent discussions will be limited to VOC control by carbon adsorption.

CARBON ADSORPTION APPLICATIONS AND PERFORMANCE

Carbon adsorption technology is used in a wide variety of applications, ranging from low-volume/low-concentration air purification to high-volume/high-concentration solvent recovery, the latter representing the focus of this program. An estimated 12,000 solvent recovery systems are in use in the U.S., in a large number of industries including many of those shown earlier in Table 4-1. Approximately 2,000 solvent recovery systems are classified as being of major size, handling air flows ranging from 7.1 to 240 Nm^3/sec (15,000 to 500,000 scfm). The remaining 10,000 units are typically package units and are used in applications treating lower air flows (2).

Solvents and organic materials recovered include: acrylates, alcohols, aldehydes, aliphatics, aromatics, ethers, ketones, naphtha, tetrahydrofuran, and chlorinated solvents including freons. Recovery can be performed for both water soluble and insoluble organics. The recovered solvent can be directly reused in the process, sold or disposed as a waste product, or distilled on-site as reclaim to the coating process.

In determining the technical applicability of carbon adsorption for control of VOC emissions from a process, several general criteria should be considered. These criteria can be briefly summarized as follows (1):

(1) The molar volume of the VOC should be in the range of 80 to 190 cm^3/gm-mole.

(2) The VOC concentration can range from 10 ppmv to near 50 percent of the lower explosive limit (LEL).

(3) The VOC-laden gas stream should be either free or easily filtered of particulate matter.

(4) The VOC-laden gas stream should be controllable to 50 to 60 percent relative humidity or less.

(5) The temperature of the VOC-laden gas stream should be controllable to 54°C (130°F) or below.

These technical criteria, along with economic and regulatory considerations, determine the applicability of carbon adsorption technology for specific situations.

Typical Process Description

For the purposes of this section, a typical carbon adsorption system used in a solvent recovery application is shown in Figure 4-2. The system features three horizontal flat carbon beds. Most systems use either two or three beds.

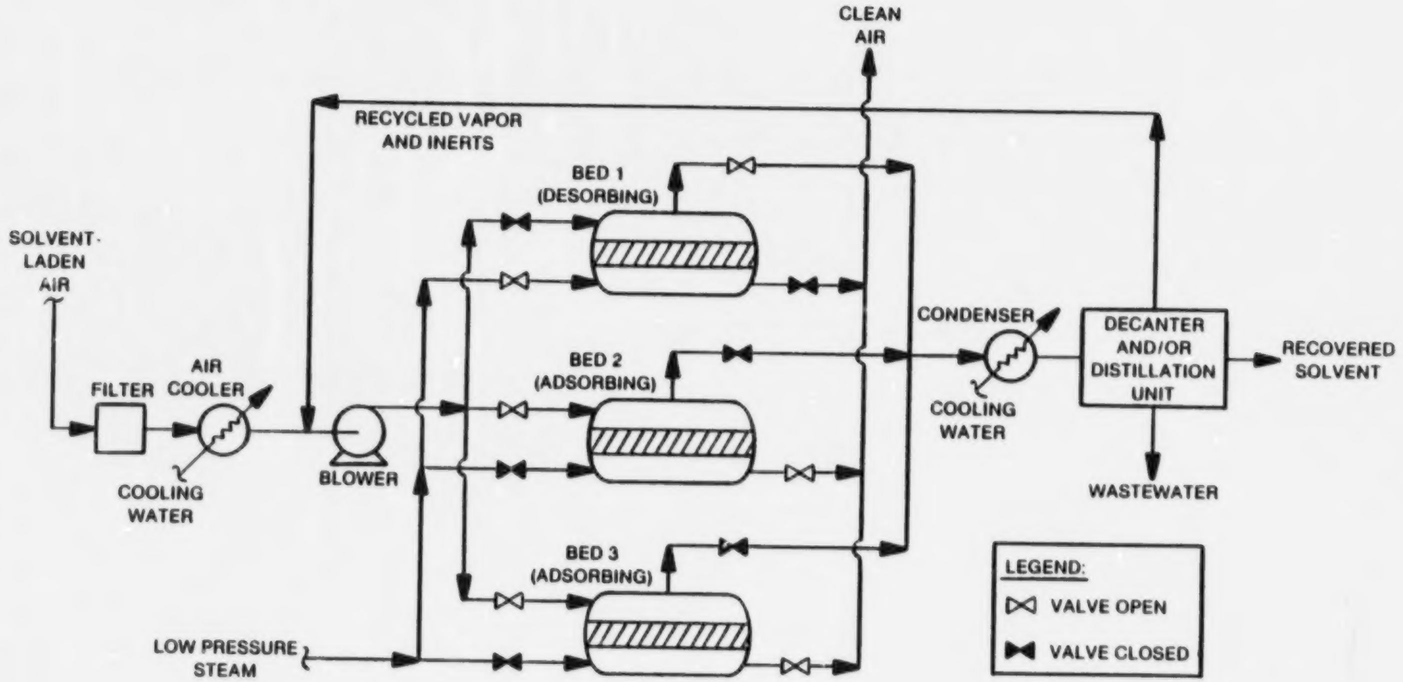
CLEAN AIR
RECYCLED VAPOR AND INERTS
BED 1 (DESORBING)
SOLVENT-LADEN AIR
FILTER
AIR COOLER
COOLING WATER
BLOWER
BED 2 (ADSORBING)
BED 3 (ADSORBING)
LOW PRESSURE STEAM
CONDENSER
COOLING WATER
DECANTER AND/OR DISTILLATION UNIT
RECOVERED SOLVENT
WASTEWATER
LEGEND:
VALVE OPEN
VALVE CLOSED

Figure 4-2. Typical three-bed carbon adsorption system flow diagram.

Horizontal canisters are typical of systems larger than 10,000 scfm. For smaller systems, the canisters may be vertical. More beds and other geometries (e.g., annular beds) can be used to increase capacity or vary system design. Fluidized bed designs are also offered; however, examination of this technology is beyond the scope of this report.

Solvent-laden air (SLA) is ducted from the manufacturing process (coating ovens, degreasers, process vents, etc.) to the solvent recovery system in concentrations ranging up to 50 percent of the LEL. For most organic solvents, inlet concentrations are typically 5,000 parts-per-million-by-volume (ppmv) or less. The SLA is filtered of particulate matter, cooled (if necessary) to 50°C (120°F) or less, and blown into the upper plenums of the adsorbing vessels (Beds 2 and 3 in Figure 4-2). The vessels contain activated carbon typically 20 to 50 inches in depth which is supported on a perforated screen. The vessels are typically of stainless steel construction with a more corrosion-resistant metal such as titanium used for the internal supports and screens. The ducting can be carbon steel, lined carbon steel or stainless steel, depending on the anticipated service.

When a bed becomes saturated with solvent, it is removed from adsorption service and desorbed with low-pressure steam (as shown in Bed 1 in Figure 4-2). Steam can be supplied by a dedicated boiler or by some other steam source. The steam and solvent vapors are condensed and then decanted (for water-insoluble solvents) or distilled (for water-soluble solvents). The condenser is made of stainless steel generally more resistant than the adsorber vessel. The decanter and distillation columns are also usually stainless steel.

If the recovered solvent is of reasonably pure quality, it is recycled to the manufacturing process. Often a blending operation is performed to obtain the desired characteristics for direct reuse of the recovered solvent. If the recovered solvent cannot be reused, it is stored and sold to a recovery operation or burned as fuel.

Typical Process Operation

Operation of the three beds in Figure 4-2 is cycled so that the beds alternate duty in the adsorption and regeneration modes. For example, when Bed 2, currently adsorbing, becomes saturated with solvent, it is removed from adsorption service and steam is introduced to the bed. After desorption, steam flow to the bed is discontinued, and the bed is depressured and allowed to "idle," i.e., cool by expansion and radiation. After the idle period, Bed 2 is again opened to SLA or some other "cool" gas. The still-hot, moisture-laden bed is cooled further and dried by the SLA as it begins its adsorption mode, and the cycle is repeated. Beds 1 and 3 operate on identical cycles, but the cycles are staggered in time in a merry-go-round fashion. Therefore, at any given time, two beds are open to SLA -- one in the first half of its adsorption mode and one in the latter half. The third bed is being desorbed or idled. A typical complete three-bed cycle may last 120 minutes: 80 minutes for adsorption, 30 minutes for steam desorption, and 10 minutes for off-line cooldown per bed. Table 4-2 shows the activities of each bed of a three-bed system during the 120-minute cycle period.

The cycle sequencing can be controlled by two methods: (1) a hydrocarbon analyzer or (2) a timer. In the first method, a hydrocarbon analyzer samples air in the bed outlet manifold. When an on-line bed in the latter half of its adsorption mode, e.g., Bed 2 in Figure 4-2, becomes saturated, solvent "breakthrough" is detected by the analyzer. Breakthrough is an increase in the VOC concentration in the carbon bed outlet which is caused by the solvent wave front emerging from the bed. The saturated bed is immediately removed from adsorption service and is opened up to desorbing steam flow. Simultaneously, the previously-regenerated and cooled bed, Bed 1 in Figure 4-2, is opened up to SLA. After a period of time, breakthrough will again be detected, and the newly saturated bed, Bed 3, will be regenerated.

The second control method uses a timer to periodically switch the beds between adsorption and desorption modes. A properly designed and operated timed system will generally remove beds from adsorption duty just before or as

TABLE 4-2. TYPICAL BED-SWITCHING SCHEDULE FOR THREE-BED CARBON ADSORPTION SYSTEM

Time (min)	Bed 1	Bed 2	Bed 3
30	Desorb	Adsorb	Adsorb
10	Cooldown	Adsorb	Adsorb
30	Adsorb	Desorb	Adsorb
10	Adsorb	Cooldown	Adsorb
30	Adsorb	Adsorb	Desorb
10	Adsorb	Adsorb	Cooldown
120			

breakthrough occurs. This is often difficult to achieve, which results in many timed bed systems being either over- or under-utilized.

More complete regeneration may increase removal efficiency, but at the expense of excessive steam consumption. Shorter desorption periods will reduce steam consumption, but solvent losses will be greater. Therefore, cycle timing is optimized when the combined costs of adsorption and regeneration are minimized. Major carbon adsorption system operating costs result from solvent losses, operating labor, desorbing steam consumption, blower motor electrical energy, and condenser cooling water. These costs, combined with the solvent type, solvent cost, solvent concentration, SLA flow rate, quality of recovered solvent, makeup solvent requirements, wastewater treatment, and capital cost of the system determine the economic feasibility of carbon adsorption for solvent recovery.

Adsorption Mode--

In horizontal bed systems, SLA typically flows downward at 0.15 to 0.50 m/sec (30 to 100 ft/min) through the carbon beds. Flow direction is typically downward to ensure proper flow distribution and to minimize agitation and attrition of the upper layer of carbon granules. For typical bed depths of 50 to 125 centimeters (20 to 50 inches), gas-phase residence times range from 1 to 8 seconds. Insufficient residence times reduce VOC removal efficiency, but excessive residence times require an inordinately oversized bed and produce high pressure drop (1). Solvent removal efficiencies by the activated carbon typically exceed 95 percent for a properly designed and operated system (3).

During the adsorption cycle the inlet concentration may vary while the outlet concentration is relatively constant. In most systems there is a slight increase in the VOC concentration at the start of the adsorption cycle due to the relatively poor adsorption capability of the warm, moist regenerated bed. This increase lasts several minutes until the bed is cooled and dried. At the end of the adsorption period, the solvent concentration increases past a pre-set level known as the breakthrough level. In some systems where the mass transfer zone in the bed is short, the increase in concentration at breakthrough is rapid. In other systems, the increase is more gradual.

Desorption Mode --

Steam used for bed regeneration performs two functions: (1) it provides the heat of desorption and (2) it acts as a diluent, lowering the partial pressure of the solvent. Economic considerations limit the degree of regeneration in solvent recovery applications. The solvent and possibly other higher molecular weight compounds remaining in the bed after desorption are called the "heel" and typically represent up to 50 percent of the carbon's adsorption capacity.

For regeneration, steam is introduced countercurrent to the direction of the SLA flow and at about 10 to 20 percent of its velocity (3). This countercurrent steam flow sweeps solvent from the effluent or relatively "clean" end of the carbon bed to and through the "contaminated" end, significantly reducing desorption time and cost.

Typically, low-pressure saturated steam, i.e., less than 50 psig, is used for desorption. Higher pressure or superheated steam is not necessarily more effective since higher temperature steam retards cooldown and may promote carbon bed fires when the bed is opened up to SLA while still fairly hot. Typical solvent recovery systems required 2 to 6 kg steam/kg of recovered solvent (2 to 6 lb steam/lb solvent).

The desorption steam/desorbed solvent vapor flows from the regenerating bed to a condenser cooled with process water or chilled water. Uncondensed vapors are recycled to the inlet of the absorbing bed(s) to provide additional VOC recovery. The condensed liquid is separated into recovered solvent and wastewater phases. The wastewater is usually routed directly to the sewer or, if the residual solvent concentrations are high, it may be steam-stripped. If the solvent is water-insoluble, solvent/water separation is typically accomplished by decantation. If the solvent is water-soluble, a distillation step is used to separate the organic and aqueous phase. Distillation adds significantly to the capital and operating costs of the solvent recovery system.

Cooling/Drying Mode --

A variety of cooling/drying schemes is available, depending on the specific application. Choices include:

- Cooldown by radiation -- This method, described earlier for the system in Figure 4-2, does not result in complete cooldown in typical systems. Therefore, when the bed is opened up to SLA after partial cooldown, adsorption efficiency is initially poor due to high bed temperature and moisture levels (as discussed later in the section "Performance Parameters").

- Cooldown by SLA -- This method uses SLA as the cooling medium. The bed effluent air can be routed to the conenser for solvent removal, to an on-line adsorber for further purification, or directly to the atmosphere.

- Cooldown by ambient air -- Ambient air is used in some systems for bed cooldown. The cooling air can be routed back to the inlet of the on-line carbon bed(s). This method reduces or eliminates the temporary solvent "slip" observed when SLA is used to cool and dry a hot carbon bed. However, complex valving control and ductwork is required.

- Cooldown by expansion -- This method does not use an influent gas stream to cool the bed, but merely opens the bed to atmospheric pressure. The steam under pressure in the bed escapes and expands. The expansion of the bases has a cooling effect which reduces the bed temperature.

The most common cooling systems use either air or SLA flowing through the bed(s) in the same direction as the SLA flow in the adsorb mode. This insures that any sorbable component in the cooling gas will not interfere with normal adsorbtion.

Process Design Considerations

Carbon Properties --

Surface area is one of the most important carbon properties reflecting adsorption capacity. It provides an indication of the relative amount of available adsorption sites and ranges from 500 to 1,600 m^2/g. Values of 1,000 to 1,100 m^2/g are common for carbons used in solvent recovery applications in the surface coating industry (4). Surface area is determined by the Brunauer-Emmett-Teller (BET) method, as described in Section 5.

A related property is the carbon's pore size/volume distribution; pore size influences molecular packing density. For most solvent recovery applications, the majority of adsorption occurs in micropores less than 40 Å in diameter. Pores of this size are large enough to allow molecular penetration yet are small enough to exhibit relatively strong adjacent- and opposite-wall attractions. Micropores typically represent about 95 percent of a carbon's surface area and 50 percent of the total pore volume. Macropores, which are generally larger than 1,000 Å, provide access to micropores and also participate in adsorption at higher solvent concentrations.

Micropore volume is indirectly measured by a standard procedure known as the carbon tetrachloride (CCl_4) activity test. CCl_4 activity is defined as the ratio (in percent) of the weight of CCl_4 adsorbed by a carbon sample to the weight of the sample. (This test is also discussed in Section 5.) Virgin activated carbons used in solvent recovery applications typically have CCl_4 activities of 50 to 60 percent. The volume of CCl_4 adsorbed is approximately equal to the volume of the carbon sample's micropores.

Carbon particle size distribution also influences carbon adsorption system performance. In general, finer carbons have more exposed surface area for increased adsorption capacity. However, fine carbons increase flow resistance (pressure drop) through the bed. Pressure drops are generally 0.82 to 8.2 kPa per meter (1 to 10 inches H_2O per foot) of carbon bed (2).

Solvent Properties --

Adsorption capacity of a carbon, i.e., maximum weight of solvent adsorbed per unit weight of carbon, is dependent on a number of solvent properties:

- polarity;
- the liquid molar volume at the solvent's boiling point (cm^3/mole), which is related to the solvent's molecular weight and boiling point; and,
- heat of adsorption.

As discussed earlier, activated carbon is a nonpolar adsorbent which preferentially attracts nonpolar molecules. For a mixed formulation of solvents, the more nonpolar compounds will be more strongly adsorbed.

Another key solvent property is the molar volume, which is generally directly proportional to molecular weight and boiling point for most industrial solvents. Typical adsorbed solvents have molar volumes from 80 to 190 cm^3/mole, with the higher molar volume compounds more readily adsorbed. Lighter solvents, i.e., those having molar volumes less than 80 cm^3/mole, are poorly adsorbed. If a mixed formulation of solvents is introduced to a carbon adsorption system, solvents with high molar volumes will generally displace adsorbed solvents of lower molar volume. An adsorption concentration profile for a three-solvent mix is shown in Figure 4-3 (1). In this system, Solvent 1 has a greater molar volume than Solvents 2 and 3, which have been displaced. The adsorption mass transfer zone of Solvent 1 corresponds to the displacement mass transfer zone of Solvent 2.

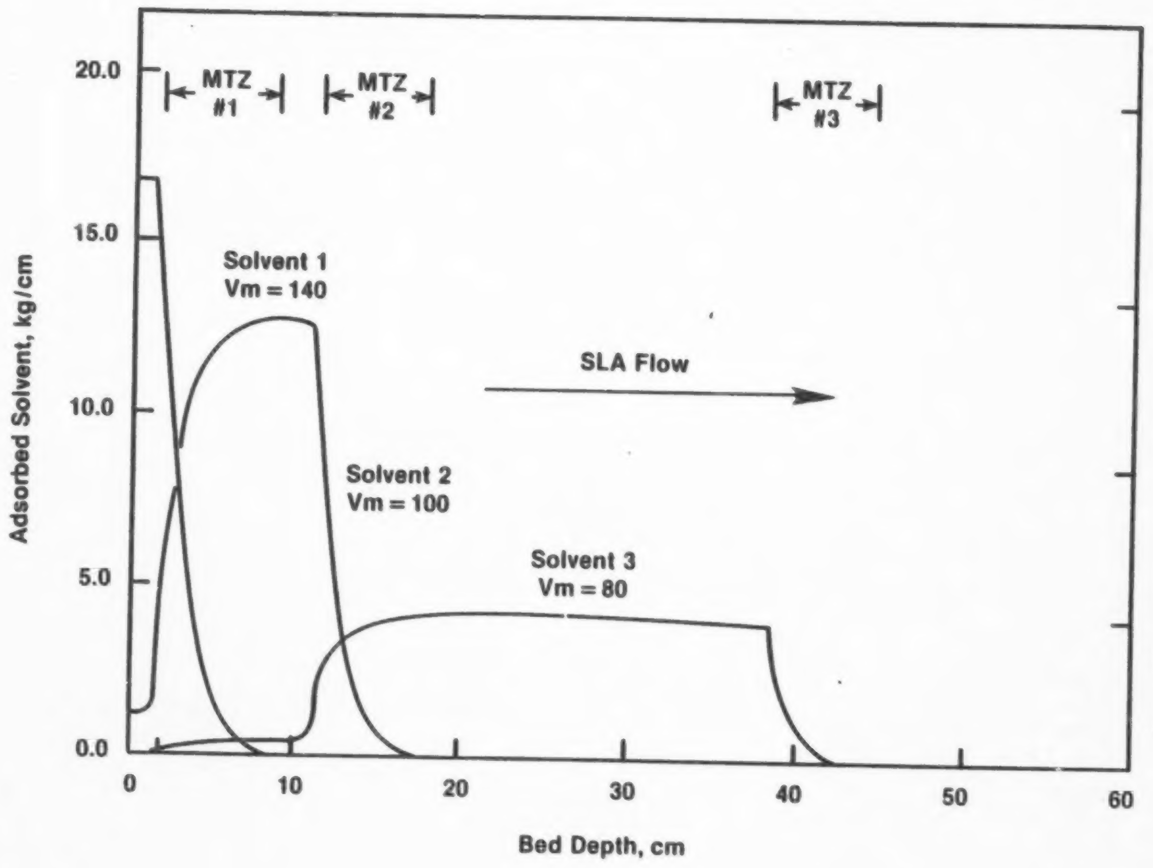

Figure 4-3. Vapor profiles in carbon bed - three-solvent mix.

The heat of adsorption of the solvent also directly affects adsorption. Adsorption is an exothermic reaction, and typical heats of adsorption are 100 to 170 cal/kg (200 to 300 Btu/lb) of vapor adsorbed (5). However, certain solvents (including phenol, certain ketones, aldehydes, and organic acids) have significantly higher heats of adsorption. Higher heat release rates (particularly with high concentration SLA streams) can cause high bed temperatures which inhibit solvent removal and increase the possibility of bed fires.

Higher boiling point compounds (such as resinous compounds and products of thermal breakdown of process solvents) have molar volumes greater than 190 cm^3/mole. These compounds are difficult to desorb and may foul the carbon, causing losses in activity. This fouling phenomenon is a primary negative factor in carbon life. Some process applications have demonstrated carbon lives of ten years or greater, while other applications have carbon lives of a few months.

Solvent Concentration --

As solvent concentration (partial pressure) increases, the average time that solvent molecules reside on the carbon surface increases, therefore increasing the probability that adsorption will occur. This phenomenon is shown in the isotherm data where the capacity is represented as a function of concentration at constant temperatures. There is a direct relationship between concentration and carbon capacity which illustrates an important feature of activated carbon. As the concentration diminishes, the carbon's capacity does not decrease significantly. Therefore, at very low VOC concentrations, as represented by many odor and toxicity problems, the working capacity remains relatively high. As adsorption capacity increases at higher concentrations, adsorption time per bed decreases. Also, regeneration efficiency is improved because, conversely, adsorption at low solvent concentration results in lower bed capacity and higher operating costs. In addition, low concentration SLA streams indicate that the ductwork, fans, and carbon adsorbers may be oversized and representative of excessive capital expenditure. Although adsorption capacity is increased with high solvent loadings, SLA solvent concentration is typically limited to about 25 to 50 percent of the LEL for safety reasons. For common solvents, this corresponds to approximately 5,000 ppmv.

Inlet Temperature --

At lower bed inlet temperatures, molecular activity of solvent vapor at the carbon surfaces is decreased, resulting in an increased average surface residence time for the solvent molecules. Therefore, probability of adsorption is greater at lower temperatures. Analytical results indicate that adsorptive capacity varies inversely as the temperature squared. Therefore, performance drops off dramatically at increased temperatures. The SLA air is often ducted from high-temperature coating ovens or dryers which operate at 65 to 120°C (150 to 250°F) or higher. The SLA is typically reduced in temperature to 49°C (120°F) or less in water-cooled precoolers before it is introduced to the carbon beds.

Inlet Relative Humidity --

Although activated carbon preferentially adsorbs nonpolar compounds, water vapor (and even air and carbon dioxide) competes to some extent for adsorption sites. For typical carbons, water vapor in SLA streams corresponding to relative humidities exceeding about 50 percent can provide significant competition with solvent for adsorption capacity. This was shown earlier in Figure 3-5. For SLA streams with relative humidities approaching saturation conditions, dehumidification is often required and may consist of a series of SLA coolers (to remove water) and reheaters or the addition of dilution air, if the dilution air is significantly drier than the SLA stream. Both of these options increase the size, cost, and complexity of the adsorption system.

The significant effect of inlet temperature and humidity on adsorption capacity causes system performance to be highly dependent on climatic conditions, since the SLA is most often essentially ambient air. System performance typically suffers on hot, humid days. In fact, long-term solvent usage data from different plants reflect seasonal swings, with high solvent recovery and low make-up requirements in cooler months and poor recovery efficiency in warm, humid months.

Carbon Service Life --

Available literature (1,2,3,5,6) was examined to discover if length of carbon service had a significant effect on system operating efficiency. Data from six plants were evaluated in terms of solvent recovery efficiency with time. Figure 4-4 presents a summary of the data. The time-frame shown is presented to show seasonal variations in recovery efficiency; the actual data from the various plants spanned several different years rather than the three-year period suggested by the figure.

Plant A (Plant 1 of the current study) uses methyl ethyl ketone (MEK) solvent to dissolve rubber compounds for application to a fabric substrate. The data for Plant A in Figure 4-4, although representative of operation with a fresh bed carbon charge, indicate relatively low recovery efficiencies, i.e., 20 to 40 percent. The low overall performance is attributed to: (1) low capture efficiency of the coating operation, as indicated by high solvent concentrations in the coating room, (2) inadvertant discharge of recovered solvent to the sewer through a failed-open valve in the solvent distillation unit, and (3) a relatively poor adsorber control efficiency of approximately 86 percent. The limited amount of data and the atypical operating characteristics prevent the accurate evaluation of long-term performance of the carbon adsorption system. The data are presented to show the significant reduction in performance that can result from a poorly operated system.

Plant B (Plant 2 of the current study) operates magnetic tape coating lines operated with a solvent formulation of tetrahydrofuran (THF) and toluene. The available recovery data, shown in Figure 4-4, show an average plant-wide solvent recovery efficiency of over 70 percent. Two significant trends are apparent. First, generally increasing efficiencies were measured

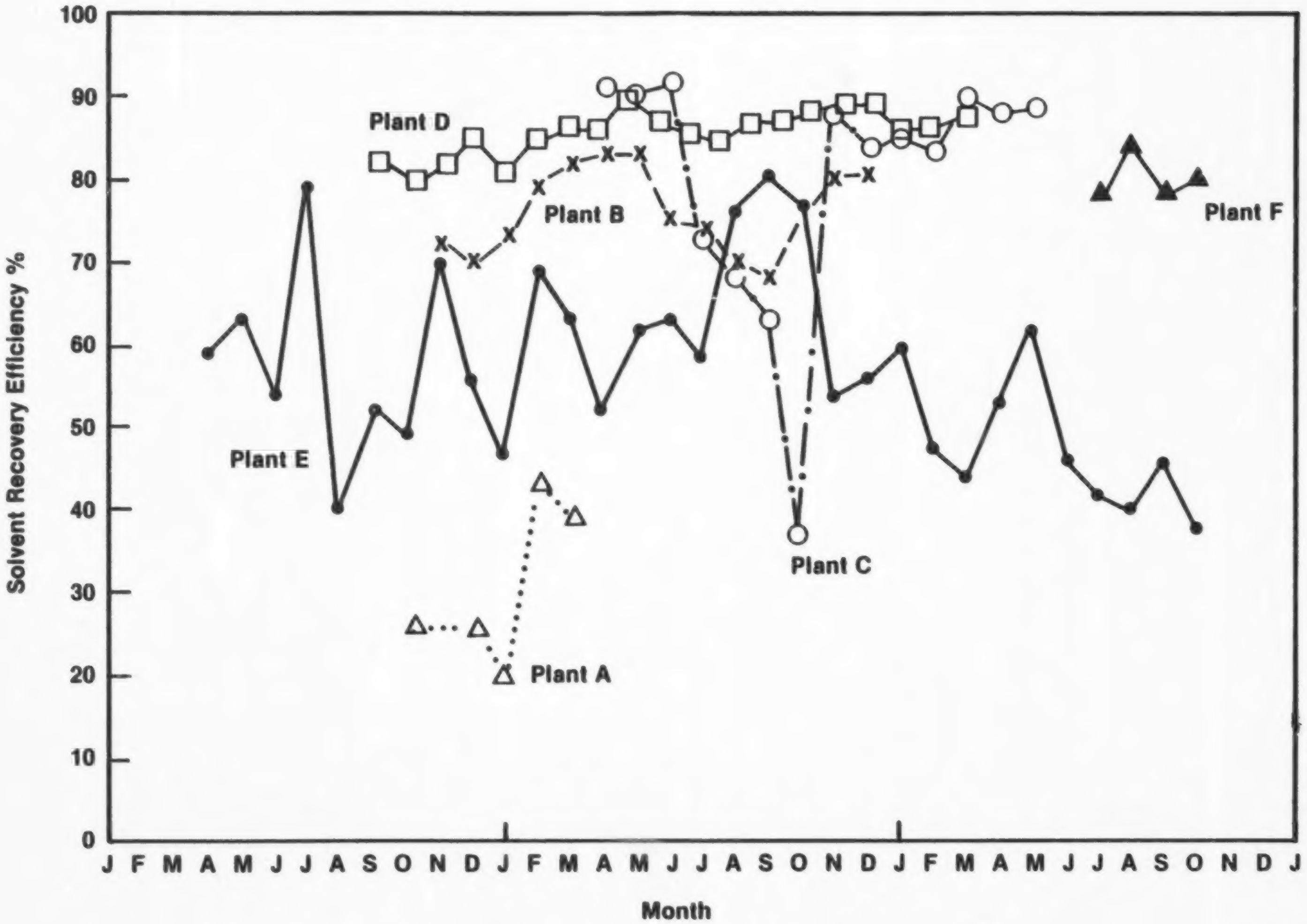

Figure 4-4. Long-term solvent recovery data.

during the first several months for which records were available, due to engineering improvements made in the operation of the solvent recovery unit. Second, the recovery data indicate a seasonal variation in efficiency, with improved performance during the cooler winter months.

Plant C coats paper with a toluene-based ink in several publication rotogravure printing presses (6). The coating operation is characterized by a unique vapor capture system, consisting of cabin-type enclosures constructed over the upper portion of each printing press. The efficient capture system contributes to the relatively high solvent recovery efficiency of the plant, which approximates 90 percent. Figure 4-4 indicates a significant decrease in performance during a four-month period which is attributable to temporary operating malfunctions of the carbon adsorption system. No decrease in performance with increasing carbon service life is apparent from the data.

Plant D also operates several publication rotogravure printing presses with a mixed naphtha-based solvent (6). Plant D also features an efficient solvent vapor capture system, with large portions of the printing/folding/storage areas within the plant ventilated to the carbon adsorption system. Solvent recovery efficiency is accordingly high, averaging almost 90 percent, as shown in Figure 4-4. The available data do not indicate decreasing performance with increasing carbon service life.

Plant E operates several rubberized fabric coating lines. Toluene is the solvent used to dissolve rubber compounds for application to the fabric web. The recovery efficiency data shown in Figure 4-4 averages less than 60 percent, with a decreasing level of performance observed over the 30-month period. No additional data are available to determine the reason for the wide fluctuations in overall solvent recovery efficiencies.

Plant F, another publication rotogravure printing operation, provided data indicating an average solvent recovery efficiency of about 80 percent (6). The limited amount of data prevents the accurate evaluation of long-term performance of the carbon adsorption system.

Miscellaneous Design and Operation Factors --

Carbon adsorption system design and operation also have a major effect on adsorption performance. The following design and operation parameters have been discussed in previous subsections:

- number and design of beds,
- cycle timing,
- timing control method (analyzer or timer),
- SLA flow rate,
- steam conditions,
- degree of regeneration, and
- cooling/drying mechanism.

Other factors affect system performance. These include maintenance practices, shutdown/startup schedules, variations or upsets in operating conditions, bed condition (e.g., channeling and degree of fouling with high-boiling compounds or particulates), pressure (adsorption capacity is directly proportional to pressure, although most systems operate at near-atmospheric pressure), degree of insulation, and characteristics of the decanter/distillation system.

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1. MSA Research Corporation, Package Sorption Device Systems Study, Final Report to U.S. Environmental Protection Agency, Contract No. EHSD 71-2, Washington, DC (April 1973).
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5. Smisek, M. and S. Cerny, Active Carbon: Manufacture, Properties and Applications, Elsevier Publishing Company, Amsterdam (1970).
6. "Publication Rotogravure Printing - Background Information for Proposed Standards," EPA-450/3-80-031a, U.S. Environmental Protection Agency. Research Triangle Park, NC (October 1980).

SECTION 5

TESTING METHODOLOGY

The primary objective of the current program was to characterize the effects of carbon service life on long-term performance of fixed-bed, steam-regenerated, gas-phase carbon adsorption systems. Particular emphasis was placed upon obtaining test data that indicated the length of carbon service and how it related to the VOC reduction performance of the carbon bed.

The technical approach designed to fulfill this test objective consisted of the following activities:

- development of a conceptual testing strategy,
- selection of test sites,
- selection/development of test methods,
- performance of on-site testing, and
- implementation of quality assurance/quality control (QA/QC) measures.

These activities are described in the following subsections.

DEVELOPMENT OF A CONCEPTUAL TESTING STRATEGY

The test program was designed to be conducted in two phases. The first phase involved the performance testing at each of several full-scale carbon adsorption systems. The test plan design focused on the continuous monitoring of adsorber VOC control efficiency, with periodic monitoring of other system performance parameters and off-site analysis of solvent, wastewater, and carbon samples.

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The second phase of the test program was designed to measure the effects of carbon service life on system performance. The test program during this second phase focused on the repeat testing of several of the original systems 18 to 22 months after the initial testing.

SELECTION OF TEST SITES

Three criteria were used to select the test sites for the test program. These were: (1) selection of approximately two carbon adsorption systems in each of the rubberized fabric, magnetic tape, and flexible packaging industries; (2) selection of well-operated systems; and (3) selection of systems that collectively processed a variety of solvents. These plants also had to be willing to cooperate during a two-week test period and during a repeat test, if necessary.

These criteria resulted in the initial identification and screening of almost 50 carbon adsorption systems. From the 50 systems, six were chosen as test sites. Once the initial test sites were selected and the performance test completed, a single criterion was used to identify those sites to be retested: those sites for which no major operating changes (primarily carbon replacement) had been implemented since the initial test. The final selection process resulted in the following carbon adsorption system test sites and dates:

- Plant 1 -- a rubberized fabric manufacturing facility using methyl ethyl ketone (MEK) solvent, tested in January 1982;

- Plant 2 -- a magnetic tape producer using a solvent mixture of toluene and tetrahydrofuran (THF), tested in February 1982 and retested in December 1983;
- Plant 3 -- a magnetic tape producer using a solvent formulation of toluene, THF, MEK, methyl isobutyl ketone (MIBK), and cyclohexanone, tested in March 1982;
- Plant 4 -- a flexible packager using hexane solvent, tested in June 1982 and retested in November 1983;
- Plant 5 -- a rubberized fabric manufacturer using toluene solvent, tested in July 1982 and retested in November 1983; and,
- Plant 6 -- a flexible packager using a solvent formulation consisting primarily of toluene and isopropyl acetate (IPAC), tested in August 1982 and retested in November 1983.

These systems and the results of testing are described in detail in Sections 6 through 11, respectively.

SELECTION AND DEVELOPMENT OF TEST METHODS

Initially, an engineering evaluation of carbon adsorption performance parameters was conducted. The results of this evaluation were used to select overall test methods and to design a test program specific to each test site.

Within each individual test program, continuous monitoring of the VOC control efficiency of the carbon adsorption system was specified as the primary measurement effort. A continuous measurement system was chosen to accurately assess system performance as a function of changing process operating variables. These included changes in inlet solvent concentrations due to different surface coating conditions and changes in outlet solvent concentrations due to cyclic operation of the carbon adsorption systems. The VOC test method selected was analogous to the total hydrocarbon (THC) measurement technique described as EPA Reference Method 25A (1). Significant development work centered on a computerized data acquisition system for the THC analyzer.

Several other test methods were used on a periodic basis to complete the characterization of system performance. These included EPA referenced methods (e.g., for volumetric gas flow rate measurement), ASTM methods (e.g., for determination of carbon properties), and other routine test methods (e.g., temperature and pressure measurement).

Table 5-1 presents a summary of the test parameters and test methods. Major test methods are reviewed in the following subsections.

Solvent (VOC) Concentration Measurement

A continuous THC sampling/analytical system was used to measure solvent concentrations in the inlet and outlet gas streams of each carbon adsorber. A stainless steel rake-type sampling probe and inert Teflon® sampling lines were used to deliver continuous gas samples to inlet and outlet THC analyzers, as shown in Figure 5-1.

The THC analyzers operate on the flame ionization detection (FID) principle. By this method, the gas sample is introduced to an air/hydrogen flame with subsequent combustion of any organics in the gas sample. The resulting ionized combustion products establish an electrical curent in the presence of oppositely-charged electrodes. The strength of the current is directly proportional to the total amount (concentration) of organics present in the sample; therefore, the detector current output from a calibrated THC analyzer can be expressed as a total organic concentration.

TABLE 5-1. TEST METHODS AND EQUIPMENT FOR PERFORMANCE AND EVALUATION

Test Parameter	Test Method/Equipment
Carbon Data	
-Type	Plant or vendor data
-Life/Makeup data	Plant or vendor data
-Particle size distribution	Sieve analysis
-Surface area	BET Method
-Moisture content	Xylene extraction
-Condition	CCl_4 activity test, retentivity test
-Amount per bed	Plant or vendor data
-Volatiles content	Thermal extraction
Solvent Composition	
-Type	Plant data
-Hydrocarbon content	GC
-H_2O content	Karl Fischer titration
Operation: General	
-Design	Plant or vendor data
-Operation and maintenance practices	Plant data
-Problem areas	Plant data
Operation: Adsorption Mode	
-Temperature (in/out)	Thermometer
-Duct pressure	Magnehelic® gauge, inclined manometer
-Relative humidity	In-duct psychrometer
-Bed depth/bed area	Direct measurement or from plant or design data
-Velocity/Volumetric flow rate	EPA Methods 1 and 2
-Length of mode (per bed)	Direct measurement with timer
-Gas-phase VOC analysis	Byron THC Analyzer, GC
-Electrical energy consumption	Plant data
-Temperature of streams to and from air cooler	Thermometer
-Type and flow rate of coolant to air cooler	Plant or design data
Operation: Regeneration Mode	
-Steam conditions	Pressure-plant gauge or data Temperature (in/out) - thermometer or steam tables Flow rate - plant data
-Length of mode (per bed)	Direct measurement with timer
-Temperature of streams to and from condenser	Thermometer
-Condenser coolant type and flow rate	Plant or design data
-Wastewater analysis (hydrocarbon dissolved in water)	GC
-Wastewater flow rate	Direct measurement
Operation: Cooling/Drying Mode	
-Medium/Method	Observation
-Temperature (in/out)	Thermometer
-Pressure	Magnehelic® gauge, inclined manometer
-Moisture content (in/out)	In-duct psychrometer
-Velocity/Volumetric flow rate	EPA Methods 1 and 2
-Length of mode (per bed)	Direct measurement with timer
-Gas-phase analysis	Byron THC Analyzer, GC

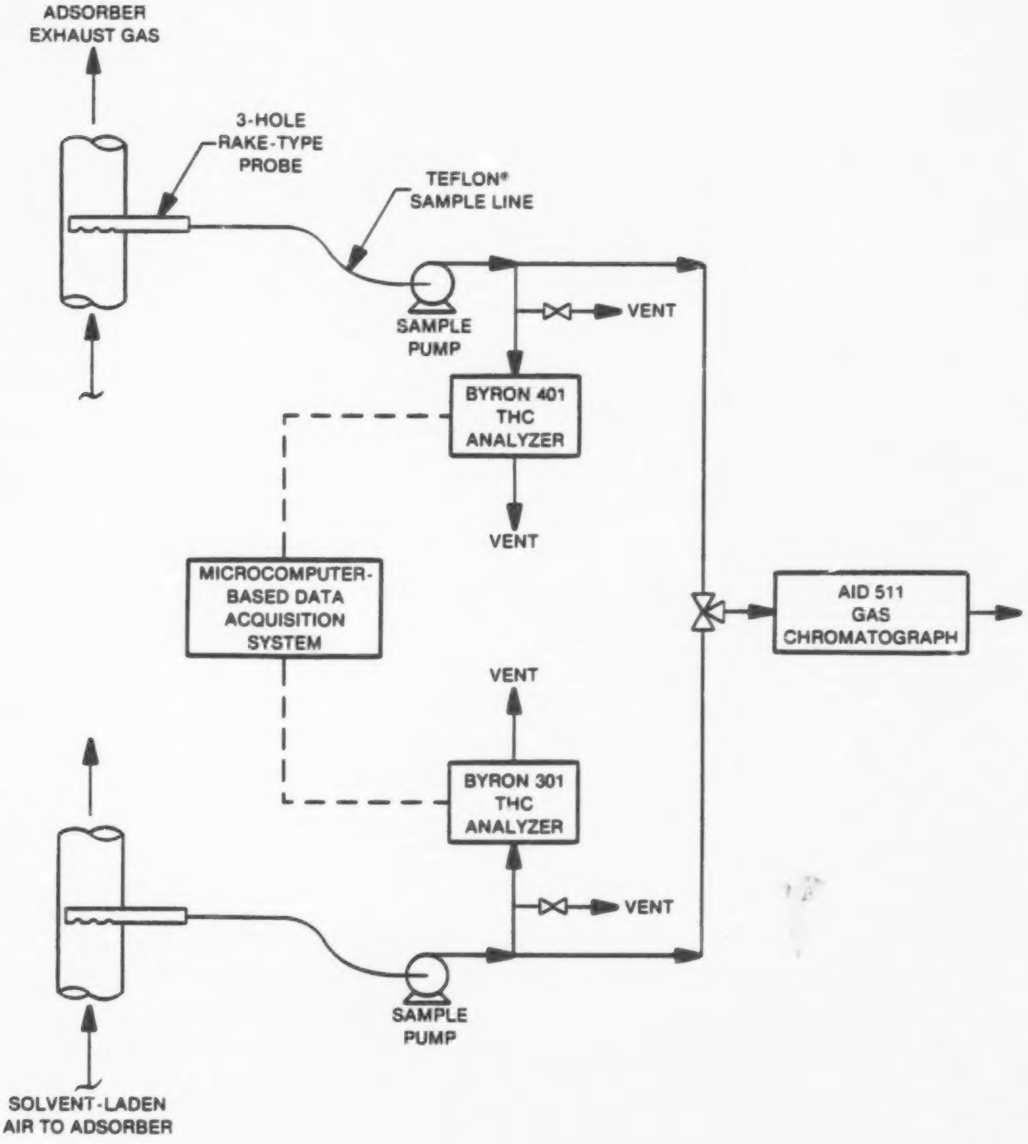
ADSORBER EXHAUST GAS
3-HOLE RAKE-TYPE PROBE
TEFLON® SAMPLE LINE
SAMPLE PUMP
VENT
BYRON 401 THC ANALYZER
VENT
MICROCOMPUTER-BASED DATA ACQUISITION SYSTEM
AID 511 GAS CHROMATOGRAPH
VENT
BYRON 301 THC ANALYZER
VENT
SAMPLE PUMP
SOLVENT-LADEN AIR TO ADSORBER

Figure 5-1. VOC sampling and analytical system.

A Byron Model 301 THC analyzer and a Byron Model 401 THC analyzer were used to measure THC concentrations of the adsorber inlet and outlet gas streams, respectively, providing data at three- and one-minute intervals. The analyzers were calibrated with multiple concentration levels of certified gas standards simulating the actual process streams to be analyzed, i.e., appropriate concentrations of solvent(s) in air. The analyzer calibration and process sampling data were automatically monitored, reduced, and stored by a microcomputer-based data acquisition system. Software for the acquisition system was developed as part of this program.

In addition to these THC measurements, a limited amount of gas-phase data was collected at selected plants using an FID-based gas chromatograph (GC) in a manner similar to EPA Draft Method 18 (2). The instrument used was a portable AID Model 511 GC. The GC technique was used to speciate the major organic components of the inlet and outlet gas streams. Speciation of the inlet SLA allowed confirmation of the plant-reported solvent composition. Speciation of the exhaust air showed the partitioning effect of activated carbon on various solvents.

Volumetric Gas Flow Rate Measurement

Measurement of the carbon adsorption system process gas flow rates was performed using EPA Reference Methods 1 and 2 (3,4). By these methods, gas velocity is calculated using: (1) the average gas temperature and velocity pressure as determined by a pitot tube traverse of the duct, (2) the wet molecular weight, and (3) the static pressure of the gas. The adsorber inlet and outlet gas flow rates were multiplied by their corresponding VOC concentration data to yield inlet and outlet VOC mass flow rates. VOC control efficiencies were calculated using the following equations:

$$M = (C)(Q)(MW)(K) \qquad (5\text{-}1)$$

where: M = VOC mass rate, kg/hr
C = VOC concentrations, parts-per-million-by-volume (ppmv)
Q = gas volumetric flow rate, Nm^3/sec
MW = VOC molecular weight, g/g_{mole}
K = multiplying factor for resolution of units;

and

$$CE = (M_{in} - M_{out})/Min * 100\% \tag{5-2}$$

where: CE = VOC control efficiency, percent
M_{in} = inlet VOC mass rate, kg/hr
M_{out} = outlet VOC mass rate, kg/hr

Carbon Analysis

Samples of virgin and used bed carbon were collected for: (1) carbon tetrachloride (CCl_4) activity and retentivity testing, (2) surface area determination, (3) volatile content, (4) moisture content, and (5) particle size distribution analysis.

Carbon samples were subjected to CCl_4 activity testing according to ASTM D3467 (5). CCl_4 activity is an indirect measure of the pore volume of an activated carbon and, therefore, the carbon's adsorption capacity. CCl_4 activity is defined as the ratio (in percent) of the weight of CCl_4 adsorbed by a carbon sample to the weight of the sample, when the carbon is saturated with CCl_4 under conditions listed in the method.

The CCl_4 retentivity testing determines the relative desorptive capability of activated carbons. In this test, dry air at specified conditions flows through a CCl_4-saturated carbon sample. The amount of CCl_4 remaining on the sample after a specified time period is compared to the weight of the virgin carbon to yield the retentivity value and, therefore, information about the relative ease of regeneration of the carbon.

The specific surface area of the fresh carbon used at each plant was determined by the Brunauer, Emmett, and Teller (BET) method, or ASTM C819 (6). The surface area available for adsorption is directly related to a carbon's solvent removal efficiency. The method, which is based upon the adsorption of nitrogen at its boiling point, is a standard carbon analysis technique used for relative comparisons of carbon adsorption capacity.

Selected virgin and bed carbon samples were thermally desorbed at 600°C to determine the weight loss or volatile content of the carbon. The moisture portion of the volatilized matter was accounted for by the xylene extraction method of ASTM D2867 (7).

Determination of particle size distribution for virgin and used carbon from each plant was performed according to ASTM D2862 (8). Carbon particle size distribution indicated the degree of attrition of the bed.

Solvent Analysis

Recovered and virgin solvent samples were collected and analyzed for organic composition and water content. These analyses were performed to determine the level of contamination of recovered solvent as compared to virgin solvent.

Comparison of the organic chemical composition of recovered and virgin solvent was performed via gas chromatography/flame ionization detection (GC/FID) analysis. The concentration of water in the virgin and recovered solvent was estimated by the Karl Fischer titration method, or ASTM D1364. (9).

Wastewater Analysis

Wastewater generated by condensation of carbon bed stripping steam was analyzed by GC/FID techniques to quantify its level of organic contamination. The results of the analyses were used to estimate the percentage of solvent lost in the wastewater.

Other Analyses

A variety of miscellaneous measurements was performed at each plant, depending upon site-specific data requirements. These analyses included: temperature and pressure measurements, monitoring of coating conditions, and measurement of physical dimensions.

In addition, cost estimates were developed for each tested carbon adsorption system based upon data provided by the participating plants. The data were compiled and expressed on a common basis for the comparison of capital and operating costs.

PERFORMANCE OF ON-SITE TESTING

As discussed previously, the testing approach included two phases -- an original testing period and a repeat testing period. Testing methodologies were identical during the two test periods.

The original testing, performed in early- to mid-1982, included two to four weeks of testing at each of six test sites. Continuous VOC concentration monitoring was conducted on a 24-hour basis, except during daily calibration periods. Other testing activities were performed on a periodic basis throughout the original test period at each plant.

The objective of the repeat testing was to measure the degradation, if any, in VOC control performance as a function of carbon service life. Therefore, an attempt was made to select for repeat testing those systems for which changes in performance levels could be demonstrated, i.e., systems whose independent operating variables had not been significantly altered.

This approach to selecting repeat test sites eliminated those systems operated by Plants 1 and 3, since their bed carbon had been replaced after the original testing. The four remaining systems (Plants 2, 4, 5 and 6) were selected for repeat testing. However, at least minor operational changes had been implemented at each of the four plants. These changes tended to obscure the relationships between carbon service life and system performance.

IMPLEMENTATION OF QA/QC MEASURES

A QA/QC protocol specific to this test program and these test methods was designed and followed to ensure the integrity of the program results. The QA/QC program is a direct result of the required EPA QA/QC procedures. These procedures include: daily calibration of the continuous monitors, multiple analyses for precision determination, quality control checks and standards for day-to-day system checks, and an independent sample system audit.

REFERENCES

1. EPA Proposed Method 25A, "Determination of Total Gaseous Organic Concentration Using a Flame Ionization Analyzer." Proposed Revision to Appendix A to 40 CFR, Federal Register, Vol. 45, No. 194. December 17, 1980, pp. 83149-83151.

2. EPA Draft Method 18, "Measurement of Gaseous Organic Compound Emissions by Gas Chromatography." Environment Reporter. Bureau of National Affairs, Washington, DC. November 25, 1983, pp. 245-261.

3. EPA Reference Method 1, "Sample and Velocity Traverses for Stationary Sources." Appendix A to 40 CFR, Environment Reporter. Bureau of National Affairs, Washington, DC. December 5, 1980, pp. 23-25.

4. EPA Reference Method 2, "Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)." Appendix A to 40 CFR, Environment Reporter. Bureau of National Affairs, Washington, DC. December 5, 1980, pp. 25-33.

5. Carbon Tetrachloride Activity of Activated Carbon, ASTM D3467, Annual Book of ASTM Standards, Part 30, 1981.

6. Specific Surface Area of Carbon or Graphite, ASTM C819, Annual Book of ASTM Standards, Part 17, 1981.

7. Moisture in Activated Carbon, STM D2867, Annual Book of ASTM Standards, Part 30, 1981.

8. Particle Size Distribution of Granular Activated Carbon, ASTM D2862, Annual Book of ASTM Standards, Part 30, 1981.

9. Water in Volatile Solvents (Fischer Reagent Titration Method), ASTM D1364, Annual Book of ASTM Standards, Part 29, 1981.

SECTION 6

TEST RESULTS - PLANT 1

The carbon adsorption system at Plant 1, a rubberized fabric manufacturer, was tested in January 1982. Design specifications and a process description for the Plant 1 system are presented in this section, followed by results of the performance testing. Capital and annualized cost data for the system are also presented.

DESIGN SPECIFICATIONS AND PROCESS DESCRIPTION

Plant 1 operates a rubberized fabric web coating line and a small fabric cord coating line. For both coating lines, methyl ethyl ketone (MEK) solvent is used to dissolve rubber compounds for application with knife-type coaters to the fabric substrate. After coating, the MEK is volatilized in drying ovens with steam-heated air. The solvent-laden air (SLA) from the ovens is conveyed to the carbon adsorption system for recovery.

The solvent recovery system consists of an adsorption section, featuring two horizontal carbon beds, and a distillation section. Design specifications for the system are presented in Table 6-1. As shown, the system is a Vic Manufacturing Company design started up on 1976. The system is designed to process an SLA flow of 5.30 Nm^3/sec (11,200 scfm) with an inlet solvent concentration of 4,050 ppmv as an MEK/toluene mixture (the effect of using a straight MEK solvent on system performance is discussed later in this section). The design solvent removal efficiency of the system is 95 percent.

TABLE 6-1. DESIGN SPECIFICATIONS FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 1

Design Parameter	Design Specification
MANUFACTURER	Vic Manufacturing Co.
STARTUP DATE	1976
CARBON BED SPECIFICATIONS	
Configuration	horizontal
Number of beds	2
Dimensions	
• length	4.9 m (16 ft)
• width	2.4 m (8 ft)
• depth	0.9 m (3 ft)
Carbon loading per bed	4,500 kg (10,000 lb)
Carbon type	Calgon BPL
Carbon base	coal
SLA SPECIFICATIONS	
Flow direction through beds	downward
Flow rate to carbon beds	5.30 Nm^3/sec (11,200 scfm)
Relative flow rate[a]	0.0012 Nm^3/sec - kg carbon (1.1 scfm/lb carbon)
Superficial bed velocity	0.44 m/sec (87 ft/min)
Residence time in bed	2.1 sec
Inlet temperature	35°C (95°F)
SOLVENT SPECIFICATIONS	
Type	60% MEK/40% toluene[b]
Inlet mass loading	261 kg/hr (575 lb/hr)
Inlet concentration loading	4,050 ppmv
Relative inlet mass loading[a]	0.058 kg/kg carbon/hr (0.058 lb/lb carbon/hr)
REGENERATION SPECIFICATIONS	
Steam consumption	1,080 kg/hr (2,375 lb/hr)[c]
Steam/recovered solvent	NA[d]
Cooling/drying medium	SLA
SOLVENT REMOVAL EFFICIENCY	95%
MATERIALS OF CONSTRUCTION	
Adsorbers	carbon and stainless steel
Ductwork	carbon and stainless steel
Piping	stainless steel
METHOD OF SOLVENT SEPARATION	decantation/distillation

[a] Refers to the solvent and SLA loadings to the carbon in the on-line (adsorbing) carbon bed.

[b] Original design specification; actual solvent is MEK.

[c] Per desorption.

[d] Data not available due to unspecified frequency of desorption.

A process flow diagram of the Plant 1 system is shown in Figure 6-1. As shown, the initial step in the solvent recovery process involves preconditioning of the SLA from the drying ovens. The preconditioning process consists of filtering, cooling, and humidifying the SLA (humidification is included to prevent bed fires). After preconditioning, the SLA is introduced to the upper plenum of the on-line adsorber. The SLA flows downward through the carbon bed, and the MEK is adsorbed by the carbon. The treated air is then exhausted through a common stack to the atmosphere.

When an on-line carbon bed completes its adsorption mode, the vessel is closed off to SLA flow, and low-pressure steam is introduced to the lower plenum of the vessel. The steam flows upward through the bed, desorbing the adsorbed MEK. The steam/MEK vapor exits the top of the vessel and is condensed. Uncondensed vapors are recycled to the inlet of the on-line bed. The condensed liquid is pH-adjusted and introduced to a steam distillation column, where the MEK and water are separated. The MEK phase is pumped to solvent storage for reuse in the coating process. The wastewater phase is discharged to the sewer.

After a bed is desorbed, it is cooled and dried with SLA, which is then exhausted to the atmosphere through the common stack. The other bed is placed into standby service during the cooling/drying period; i.e., it is closed off to SLA and steam flow. Following this step, the regenerated bed is placed into standby service, and the previously on-line bed is returned to adsorption service.

The sequencing of the adsorption/regeneration modes of the two beds is controlled by the combined action of an infrared (IR) hydrocarbon analyzer and a timer. The analyzer samples the treated air being discharged from the common stack and generates a signal to remove the on-line bed from adsorption service when the MEK breakthrough exceeds a concentration setpoint. The timer

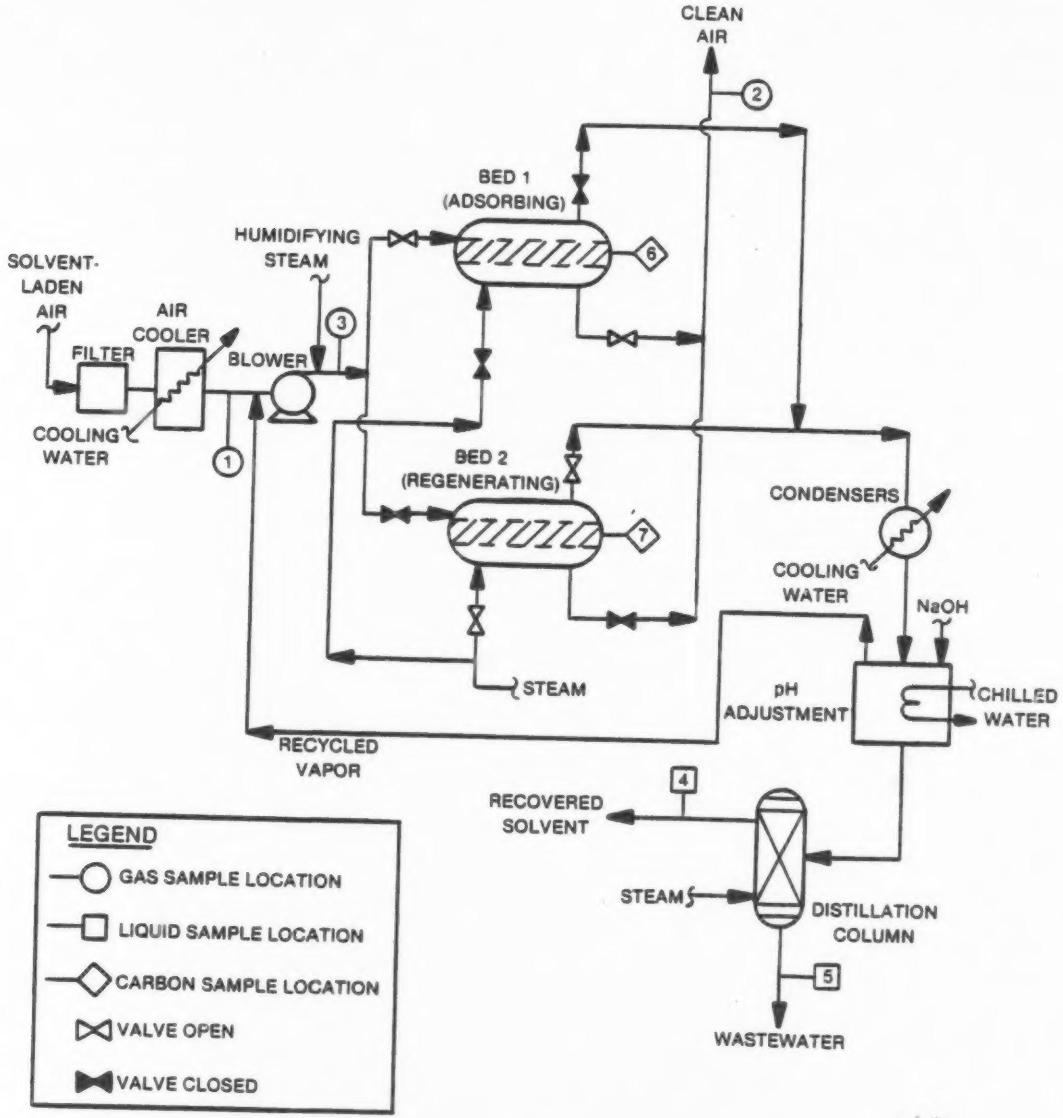
CLEAN AIR
②
BED 1 (ADSORBING)
HUMIDIFYING STEAM
SOLVENT-LADEN AIR
AIR COOLER
FILTER
BLOWER
③
⑥
COOLING WATER
①
BED 2 (REGENERATING)
⑦
CONDENSERS
COOLING WATER
NaOH
STEAM
pH ADJUSTMENT
CHILLED WATER
RECYCLED VAPOR
4
RECOVERED SOLVENT
STEAM
DISTILLATION COLUMN
5
WASTEWATER
LEGEND
GAS SAMPLE LOCATION
LIQUID SAMPLE LOCATION
CARBON SAMPLE LOCATION
VALVE OPEN
VALVE CLOSED

Figure 6-1. Plant 1 solvent recovery system.

controls the length of the steam desorption mode (55 minutes) and the cooling/drying mode (10 minutes). A complete adsorption/desorption cycle is from two to four hours in length, depending on the inlet MEK concentration. The complete cycle can be divided into the following segments:

Segment	Bed A	Bed B	Time
1	Ads	Des	55 min.
2	Std	Cool	10 min.
3	Ads	Std	0-65 min.
4	Des	Ads	55 min.
5	Cool	Std	10 min.
6	Std	Ads	0-65 min.

The solvent recovery system at Plant 1 is relatively well instrumented. The system is operated and monitored at a remote control station with the following instrumentation:

- a lighted panel indicating each bed's operating status,
- a timer indicating remaining desorption time of a desorbing bed,
- an output meter for the IR hydrocarbon analyzer,
- circular chart recorders for inlet and outlet bed temperatures and steam flow rate,
- a meter to indicate inlet relative humidity, and
- a control panel dedicated to remote operation and monitoring of the distillation section.

With the exception of the inlet relative humidity meter, all instrumentation was operational during the time of the testing.

TEST RESULTS

Testing of the Plant 1 carbon adsorption system focused on the characterization of: (1) general operating parameters; (2) VOC control performance; and (3) carbon, solvent, and wastewater properties. Results of these characterizations are presented in this section.

General Operating Parameters

General operating conditions for the Plant 1 carbon adsorption system during the test period are presented in Table 6-2. The data are categorized as adsorption and regeneration mode data.

The adsorption mode operating data show close agreement with the design specifications, in terms of SLA throughput and system temperatures. However, the adsorption mode operating conditions show a deviation from the design solvent type. The Plant 1 system, designed to process a 60/40 volume percent mixture of MEK/toluene, was actually operated to process a straight MEK solvent. In general, this operating change represented more severe adsorption conditions, as MEK is less efficiently adsorbed than toluene.

Significant results of the regeneration mode testing at Plant 1 are represented by the steam consumption rate and the steam/solvent ratio. The desorption steam flow rate for Plant 1 averaged 1,090 kg/hr (2,410 lb/hr) per bed desorption, which compares closely with the design value of 1,080 kg/hr (2,375 lb/hr). However, the steam/recovered solvent ratio of 20 kg/kg (20 lb/lb) as determined from historical plant data, is considerably in excess of typical values of 2 to 6 kg/kg (2 to 6 lb/lb). Most of the excessive solvent losses suggested by this high ratio probably resulted from a failed valve in

TABLE 6-2. GENERAL OPERATING DATA FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 1

Operating Parameter	Operating Conditions[a]
	Original Test - January, 1982
Adsorption Mode	
Solvent type	MEK
Mode length	95 min
Inlet SLA flow rate	5.39 Nm^3/sec (11,400 scfm)
SLA superficial velocity	0.45 m/sec (89 ft/min)
Bed residence time	2.1 sec
SLA temperature drop across air cooler	11°C (20°F)
Inlet SLA temperature (after air cooler)	34°C (94°F)
Inlet SLA relative humidity	39%
Carbon bed pressure drop	Bed A - 3.5 kPa (13.9 in. H_2O) Bed B - 3.4 kPa (13.7 in. H_2O)
Outlet air flow rate	5.39 Nm^3/sec (11,400 scfm)
Outlet air temperature	29°C (84°F)
Outlet air relative humidity	62%
Regeneration Mode	
Desorption period length	55 min
Cooldown period length	10 min
Standby period length	30 min
Steam flow rate (per bed desorption)	1,090 kg/hr (2,410 lb/hr)[b]
Steam/recovered solvent ratio	20 kg/kg (20 lb/lb)[c]
Steam pressure	239 kPa (20 psig)
Steam temperature	126°C (258°F)
Wastewater flow rate	320 kg/hr (700 lb/hr)[d]

[a] Average values are presented.

[b] Based on plant chart recordings.

[c] Based on historical solvent recovery and steam usage data.

[d] Integrated value, based on measured data.

the distillation section, which allowed recovered solvent to drain to the sewer. Therefore, loss of the solvent resulted in a substantial decrease in the volume of recovered solvent. Repair of the valve resulted in an estimated steam/solvent ratio of approximately 10 kg/kg (10 lb/lb). This value was still higher than typical ratios and was attributed to inadequate carbon bed control performance and fugitive solvent losses in the distillation area.

VOC Control Efficiency Performance

Summarized VOC control efficiency data for the carbon adsorption system at Plant 1 are presented in Table 6-3. The data indicate that during the original test period with five-month old carbon, inlet solvent concentrations averaged 333 ppmv, for a VOC control efficiency (mass basis) of 84.9 percent. This control level indicates a significant degradation from the design performance level of 95 percent.

The VOC control efficiency was measured on a "system" basis, therefore, the VOC recycle stream from the regenerating bed was considered to represent an internal loop of the solvent recovery system. By this approach, the control efficiency was based upon inlet SLA VOC concentrations (from the ovens) and outlet gas VOC concentrations (from the adsorption system). Inclusion of the recycle gas stream as an inlet VOC source, in addition to the SLA stream from the ovens, would have resulted in the expression of control efficiency on a "bed" basis.

The following factors contributed to the below-design VOC control efficiency of the Plant 1 solvent recovery system:

- use of SLA as a cooling medium during bed regeneration,
- relatively poor adsorption performance of Bed B,

TABLE 6-3. VOC CONTROL EFFICIENCY DATA FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 1

	Inlet VOC Loading		Outlet VOC Emissions		VOC Control Efficiency,%[b,c]
	Concentration, ppmv[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	Concentration, ppmv[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	
Original Test - January, 1982	2,190	129 (284)	333	19.5 (42.9)	84.9

[a] As MEK.

[b] Average values are presented.

[c] Efficiency expressed on a "system" basis.

- periodic overloading of the beds with uncondensed solvent vapors through the recycle line,
- excessive inlet relative humidities,
- use of a solvent that is more difficult to adsorb than the design solvent, and
- degradation of the carbon's capacity to adsorb solvents.

The effects of these factors on system performance are discussed below.

The below-design performance levels measured during the original test period are exemplified by the VOC concentration profiles shown in Figure 6-2. The upper curve in the figure represents the concentration of MEK in the SLA flowing from the drying oven to the solvent recovery system. The lower curve represents the MEK concentration in the common bed exhaust. The concentration profiles represent one complete cycle of carbon adsorber operation.

The 190-minute cycle is divided into six time segments, as described earlier. As shown in the figure, outlet MEK concentrations increased during adsorption segments 1, 3, 4 and 6 as the on-line bed became saturated with solvent. Cooling/drying segments 2 and 5 were characterized by high outlet solvent concentrations due to the hot and moist conditions of the bed immediately after steam desorption.

Excessive solvent losses through Bed B are shown by the outlet VOC concentration profile in Figure 6-2, especially during time segment 4. During this time segment, Bed A was still undergoing regeneration and was, therefore, unable to take over adsorption duty. The excessive solvent losses through Bed B were apparently related to differences in carbon adsorption capacity, which is discussed later in this section. Differential pressures were similar for

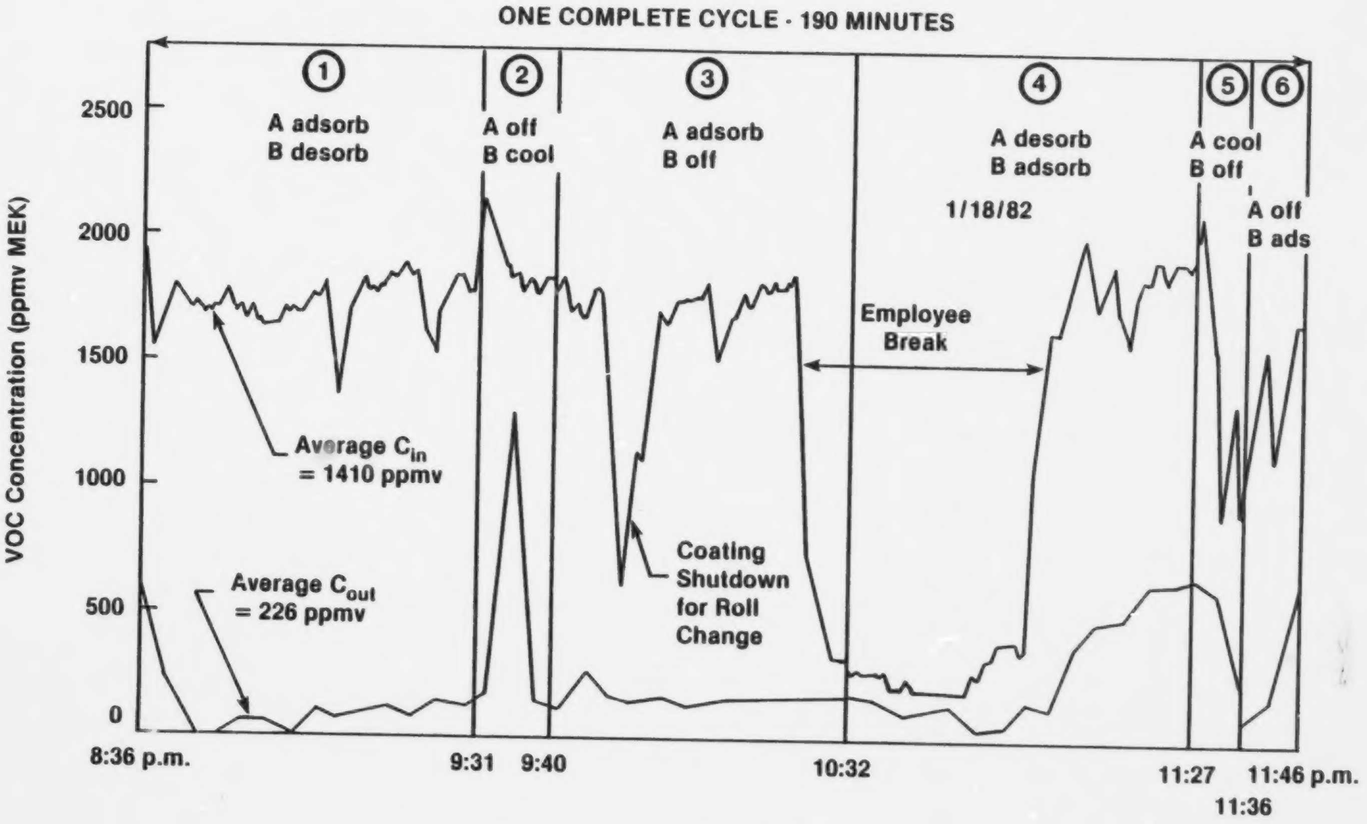

Figure 6-2. Plant 1 VOC concentration profiles.

Beds A and B; therefore, the carbon in Bed B did not appear to be channeled. For the total cycle shown in Figure 6-2, the inlet concentration averaged 1,410 ppmv, which corresponded to a solvent loading of 75.7 kg/hr (167 lb/hr). The outlet concentration averaged 226 ppmv, corresponding to an outlet VOC mass rate of 12.3 kg/hr (27.1 lb/hr). Therefore, total system control efficiency for the cycle was 83.8 percent. Comparative control efficiencies for Bed A (segments 1, 3 and 5) and Bed B (segments 2, 4 and 6) during the cycle shown were 87.2 and 78.9 percent, respectively.

As discussed earlier in this section, the Plant 1 carbon adsorption system includes a recycle line for returning inerts and uncondensed solvent vapors from the condenser to the inlet of the adsorption system. This design feature is included to maximize solvent recovery efficiency of the unit. During the test of the Plant 1 system, the condenser was unable to achieve complete condensation of the solvent vapors and steam from the regenerated bed. This condition was evidenced by the discharge of a high-temperature condensate and hot fugitive solvent vapors from the condenser during bed regeneration. As a result of the incomplete condensation, excessive amounts of solvent and water vapor were recycled to the on-line carbon bed during regeneration of the desorbing bed.

The effects of excessive VOC recycle on the carbon bed solvent loading are shown by the VOC concentration profiles in Figure 6-3. Two concentration profiles over a two-hour cycle are shown: (1) the concentration of the SLA from the drying oven (sample point 1 in Figure 6-1) and (2) the concentration of the mixed SLA/recycle stream entering the beds (sample point 3 in Figure 6-1). As shown, the inlet SLA concentration averaged 2,080 ppmv for the cycle shown. However, a solvent concentration spike (up to almost 6,000 ppmv) was introduced to the on-line carbon bed by the recycle stream during steaming of the regenerating bed. The concentration spike increased the average solvent concentration loading to the on-line bed by over 20 percent, to 2,550 ppmv. The net effect is an overloading of the adsorbing carbon bed with solvent that had been previously adsorbed.

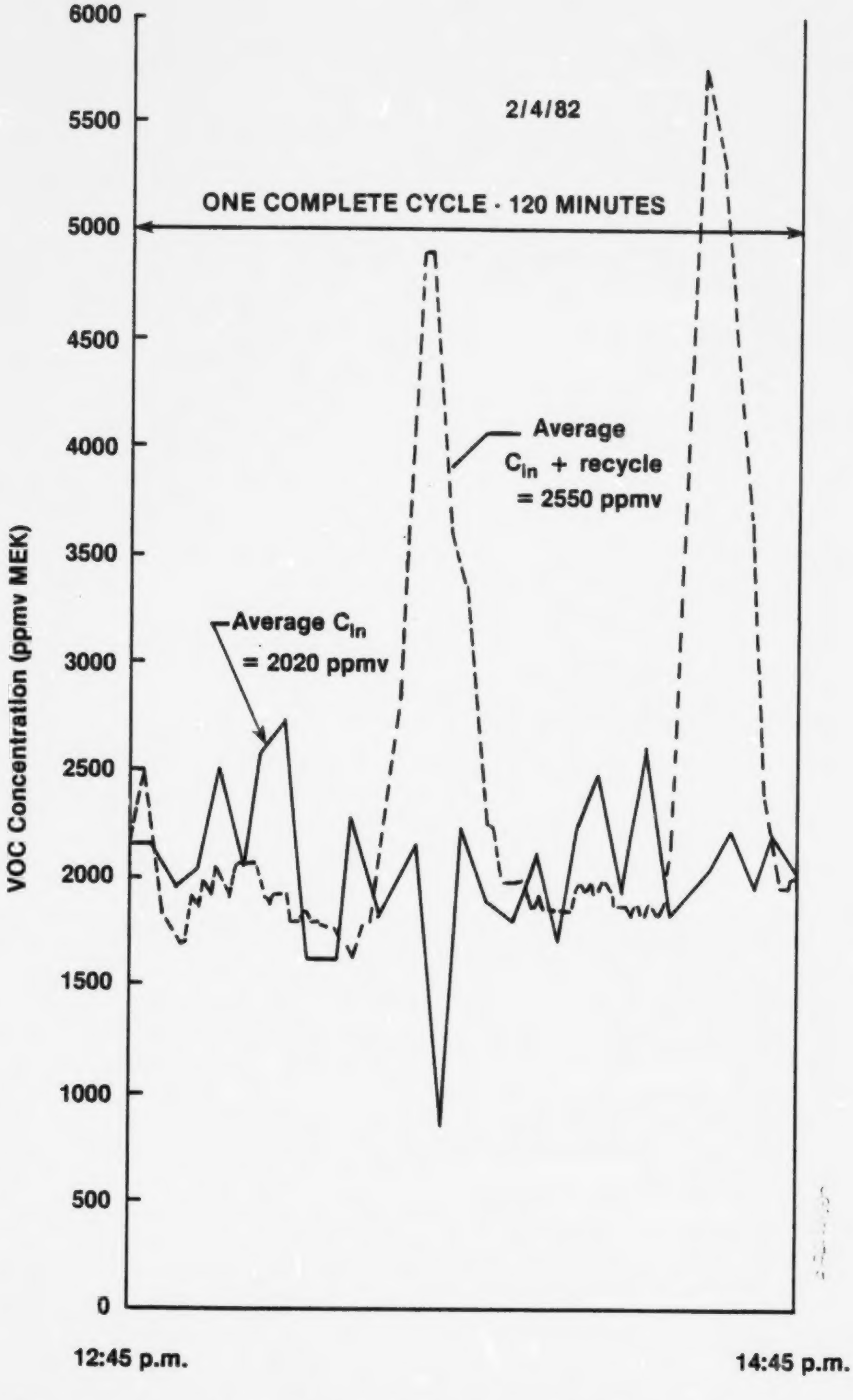

Figure 6-3. Effect of recycled MEK vapor on Plant 1 inlet concentration.

In addition to the periodic introduction of moisture-laden gas through the recycle line, excessive moisture was also introduced by the SLA humidifier upstream of the carbon beds. The humidifier, installed to prevent bed fires, was automatically controlled by a sensing element to inject low-pressure humidifying steam to maintain a design inlet relative humidity of approximately 50 percent (at inlet relative humidity levels greater than 50 percent, carbon adsorption systems suffer a significant decrease in solvent removal efficiency due to competition for adsorption sites by water vapor). However, periodic measurements of inlet moisture levels during the test period indicated that the humidifier was in operation even when relative humidity exceeded 50 percent. During these periods of off-design performance, the humidifier injected steam in amounts sufficient to result in inlet relative humidities approaching 90 percent. The introduction of excessive moisture to the carbon beds resulted in an overall reduction in solvent control efficiency.

Also apparently contributing to the below-design control efficiency of the system was the substitution of the original solvent, an MEK/toluene mixture, with the current coating solvent, straight MEK. As mentioned in Section 3, the ability of an activated carbon to adsorb a solvent is directly related to that solvent's liquid molar volume. MEK, currently used as the Plant 1 coating solvent, has a liquid molar volume of 96 cm^3/mol. Toluene, which is a major component of the design solvent formulation, has a liquid molar volume of 118 cm^3/mol. Therefore, substitution of the design solvent formulation (MEK and toluene) with the current solvent (MEK) results in lower carbon working capacities and, if no adjustments are made in the steaming rate, excessive steam consumption during regeneration.

Finally, the properties of the bed carbon indicated a possible loss of adsorption capacity. The loss in adsorption capacity may have been related to contamination by heavy organic or sulfur-bearing compounds in the coating formulation, reaction compounds formed on the bed, or compounds added to the boiler feedwater as corrosion inhibitors, scale inhibitors, softeners, etc.

Carbon, Solvent, and Wastewater Characteristics

Results of the carbon, solvent, and wastewater analyses conducted for the Plant 1 carbon adsorption system are summarized in Table 6-4 and discussed below.

The coal-based carbon in service during the original test period at Plant 1 was relatively new, having been in service for five months. However, bed carbon activity showed significant degradation from virgin carbon activity, as shown by the measured CCl_4 activity and volatiles content values. In addition, Bed B carbon showed potentially more degradation than the Bed A carbon, as determined by the CCl_4 activity and retentivity values. The results of the carbon analysis are consistent with the lower VOC control efficiencies measured for Bed B.

Particle size distribution analysis of the carbon indicated that the bed carbon consisted of finer particles than the virgin carbon. This result is attributed to carbon attrition over many adsorption/desorption cycles and to manual raking of the beds during routine bed inspections.

Analysis of virgin and recovered solvent samples indicated the presence of an unknown solvent component, i.e., an organic compound other than MEK. The nature or source of the contaminant was unconfirmed, but plant personnel and the solvent supplier indicated that the MEK solvent in storage may have been inadvertently contaminated by the delivery of an unknown hydrocarbon solvent. The contaminant represented approximately 15 percent (by weight) of the solvent samples.

The water content of the solvent samples ranged from less than 0.1 percent for the virgin solvent to nominally 9 percent for the recovered solvent. The presence of significant amounts of water in the recovered solvent ws due to incomplete separation of water and MEK (a highly water-soluble solvent) in the distillation section of the solvent recovery unit.

TABLE 6-4. CHARACTERISTICS OF CARBON, SOLVENT, AND WASTEWATER FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 1

Parameter	Original Test Period - January, 1982[a]				
Carbon Analysis[b]	Bed A		Bed B		Virgin
	Influent	Effluent	Influent	Effluent	
Service life	0.4 yr	0.4 yr	0.4 yr	0.4 yr	NA
CCl_4 activity, %	20	36	17	19	63
CCl_4 retentivity, %	8	19	12	10	43
Volatiles, %	14	8	14	9	1
Surface area, m^2/g	NM	NM	NM	NM	898
Moisture, %	8	21	7	24	10
Particle size, mm[c]					
Solvent Analysis		Recovered MEK			Virgin MEK
MEK, wt %		78.0			84.0
Unknown solvent, wt %		12.7			16.0
Water, wt %		9.3			<0.1
Wastewater Analysis					
MEK, ppm (wt)			11,200		
Other, ppm (wt)[d]			5,700		

NA = Not applicable NM = Not measured

[a] Average values are presented.

[b] Carbon samples were collected after bed desorption.

[c] Sieve size through which 50% of the carbon sample weight passed.

[d] As MEK.

Analysis of the wastewater discharged from the distillation column to the sewer indicated an average organic content of approximately 17,000 ppm by weight. This organic level represented approximately 4 percent of the total solvent entering the solvent recovery system.

COST DATA

Cost data for the Plant 1 solvent recovery system are presented in this section. Included is a list scope of equipment represented by the cost data, followed by estimated capital and annualized costs.

Equipment List for Costing

The following major equipment items are included within the cost data supplied for the Plant 1 solvent recovery system:

- SLA transport equipment, including the SLA blower and ductwork from the oven;
- SLA preconditioning equipment, including the filter, air cooler, and humidifier;
- solvent adsorption equipment, consisting of the adsorber vessels and related equipment;
- solvent separation equipment, consisting of the distillation section of the solvent recovery unit; and
- solvent storage equipment, including the virgin and recovered solvent storage tanks and piping.

Specifically excluded from the cost data are equipment items associated with solvent/coating blending, surface coating, and web drying (ovens).

Capital Costs

Capital costs for the Plant 1 solvent recovery system, expressed in late 1983 dollars, are presented in Table 6-5. As shown, the total estimated capital cost is $622,000. On a unit design flow rate basis, the total capital cost corresponds to $118,000/Nm^3/sec ($56/scfm).

Annualized Costs

Estimated annualized costs for the Plant 1 system, in 1983 dollars, are presented in Table 6-6. As shown, total costs approximate $262,000 per year, with capital recovery, steam, and labor representing the largest annualized cost components. Based on the actual solvent recovery rate measured at Plant 1, the total annualized cost corresponds to a unit cost of $0.53/kg ($0.24/lb) of solvent.

TABLE 6-5. CAPITAL COSTS FOR THE SOLVENT RECOVERY SYSTEM AT RUBBERIZED FABRIC PLANT 1[a]

DIRECT COSTS	
• Delivered equipment	$ 436,000
• Installation materials (ducting, piping, foundations, buildings, electrical, instrumentation, insulation, painting, tankage, etc.)	87,000
• Installation labor	Included above
TOTAL DIRECT COSTS (TDC)	$ 523,000
INDIRECT COSTS	
• Engineering and supervision	$ 17,000
• Miscellaneous construction expenses	31,000
• Contractor's fees	0
• Contingencies	21,000[b]
TOTAL INDIRECT COSTS (TIC)	$ 69,000
OTHER COSTS	
• Interest during construction	$ 0
• Startup	30,000[b]
• Other	0
TOTAL OTHER COSTS (TOC)	$ 30,000
TOTAL CAPITAL COSTS (TCC = TDC + TIC + TOC)	$ 622,000
RELATIVE CAPITAL COSTS	
• TCC/design SLA flow rate	$ 118,000/Nm^3/sec ($56/scfm)
• TCC/design carbon charge	$ 68/kg ($31/lb)

[a] All cost figures, unless otherwise noted, were obtained by scaling plant-supplied data to a late 1983 capital cost basis. Scaling factors were obtained from the Chemical Engineering Plant Cost Index; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

TABLE 6-6. ANNUALIZED COSTS FOR THE SOLVENT RECOVERY SYSTEM AT RUBBERIZED FABRIC PLANT 1[a]

DIRECT COSTS	
• Labor	
--operating	$ 21,000
--maintenance	5,000
--laboratory	0
--supervisory	4,000
• Maintenance materials	5,000[b]
• Activated carbon	12,000
• Utilities	
--electricity	18,000
--steam	48,000[b]
--cooling water	2,000
--chilled water	<1,000[b]
TOTAL DIRECT COSTS (TDC)	$ 116,000/yr
INDIRECT COSTS	
• Capital recovery[c]	$ 101,000[b]
• Labor and plant overhead	24,000[b]
• General and administrative	6,000[b]
• Insurance and property tax	15,000[b]
TOTAL INDIRECT COSTS (TIC)	$ 146,000/yr
TOTAL ANNUALIZED COSTS (TAC = TDC + TIC)	$ 262,000/yr
RELATIVE ANNUALIZED COSTS	
• TAC/actual annual SLA throughput	\$ 3.0/10^3Nm^3 (\$0.08/10^3 scf)
• TAC/actual annual solvent recovery	\$ 0.53/kg (\$0.24/lb)

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[a] All cost figures, unless otherwise noted, were obtained by multiplying plant-supplied unit costs (e.g., \$/man-hour) by measured or plant-supplied operating rates (e.g., man-hours/week). Costs are expressed on a late 1983 basis; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

[c] Capital recovery = $\text{TCC} \times \frac{i(1 + i)^n}{(1 + i)^n - 1}$

where TCC = total capital cost
i = interest rate @ 0.10
n = equipment life @ 10 years

SECTION 7

TEST RESULTS - PLANT 2

The carbon adsorption system at Plant 2, a magnetic tape manufacturing facility, was performance tested in February 1982 and December 1983. The Plant 2 system design specifications and process description are presented in this section, followed by results of the performance testing. Capital and annualized cost data are also presented.

DESIGN SPECIFICATIONS AND PROCESS DESCRIPTION

Plant 2 operates three magnetic tape coating lines. The coating operation involves the application of an iron oxide/solvent slurry to a polyester film sheet. The solvent, consisting of a mixture of toluene and tetrahydrofuran (THF), is volatilized from the polyester web in steam-heated ovens and is conveyed with drying air to the solvent recovery system.

The solvent recovery system features an adsorption section, consisting of three annular carbon beds, and a distillation section. Design specifications for the system are presented in Table 7-1. The Plant 2 carbon adsorption system was designed by Sutcliffe, Speakman and Company and was started up in 1980. The system is designed to handle a 6.01 Nm^3/sec (12,700 scfm) SLA stream with an inlet THF/toluene concentration of 850 ppmv. The design control efficiency is 92 percent which, when combined with the design steam consumption rate, results in a design steam/recovered solvent ratio of 7.0 kg/kg (7.0 lb/lb). This ratio is higher than reported values and is apparently related to the continuous steam flow inherent in the system's regeneration scheme.

TABLE 7-1: DESIGN SPECIFICATIONS FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 2

Design Parameter	Design Specification
MANUFACTURER	Sutcliffe, Speakman, and Co.
STARTUP DATE	1980
CARBON BED SPECIFICATIONS	
Configuration	annular (vertical)
Number of beds	3
Dimensions	
• outer diameter	1.4 m (4.5 ft)
• inner diameter	0.9 m (3 ft)
• thickness	23 cm (9 in)
• height	2.4 m (8 ft)
Carbon loading per bed	1,140 kg (2,500 lb)
Carbon type	Sutcliffe, Speakman #607
Carbon base	coconut shell
SLA SPECIFICATIONS	
Flow direction through beds	inward
Flow rate to carbon beds	6.01 Nm^3/sec (12,700 scfm)
Relative flow rate[a]	0.0026 Nm^3/sec - kg carbon (2.5 scfm/lb carbon)
Superficial bed velocity	0.31 m/sec (61 ft/min)
Residence time in bed	0.7 sec
Inlet temperature	32°C (90°F)
SOLVENT SPECIFICATIONS	
Type	50% THF/50% toluene
Inlet mass loading	64 kg/hr (140 lb/hr)
Inlet concentration loading	850 ppmv
Relative inlet mass loading[a]	0.028 kg/kg carbon/hr (0.028 lb/lb carbon/hr)
REGENERATION SPECIFICATIONS	
Steam consumption	410 kg/hr (900 lb/hr)[b]
Steam/recovered solvent	7.0 kg/kg (7.0 lb/lb)
Cooling/drying medium	—[c]
SOLVENT REMOVAL EFFICIENCY	92%[d]
MATERIALS OF CONSTRUCTION	
Adsorbers	carbon and stainless steel
Ductwork	carbon steel
Piping	carbon steel
METHOD OF SOLVENT SEPARATION	distillation

[a] Refers to the solvent and SLA loading to the carbon in the on-line (adsorbing) carbon beds.

[b] Continuous average, including distillation steam.

[c] No distinct cooling/drying made.

[d] Guaranteed.

A process flow diagram of the Plant 2 solvent recovery system is shown in Figure 7-1. As shown, the SLA is transported from the drying ovens, filtered, and cooled. After preconditioning, the SLA is conveyed to two on-line adsorbers (the third adsorber is being regenerated). The SLA is introduced to the exterior of the annular adsorbers and passes inward through the carbon, removing solvent vapors from the air stream. The treated air is exhausted from the interior of the annular adsorbers through individual exhaust stacks on each bed.

When an on-line carbon bed completes its adsorption mode, the adsorber vessel is closed off to SLA flow. Simultaneously, low-pressure desorption steam is introduced to the interior of the annular bed and flows through the bed, countercurrent to the previous SLA flow. The steam strips solvent from the carbon and exists from the exterior of the annulus. The steam/solvent mixture is then condensed, and uncondensed vapors and inerts are recycled to the inlet of the adsorption system. The condensed THF/toluene/water mixture is separated into its components in the distillation section. The recovered solvents are pumped to storage for reuse in the tape coating process; the wastewater phase is discharged to the sewer.

After desorption, the bed is immediately returned to adsorption service; i.e., there is no distinct cooling/drying mode. When the hot, moist bed comes on-line, the SLA provides the bed cooling. This results in a high VOC emission rate during the start of each absorption cycle.

The sequencing of the adsorption/regeneration modes of the three beds is controlled by a timer. During both original and repeat test periods in 1982 and 1983, respectively, each bed adsorbed for 64 minutes and was desorbed for 32 minutes. The operation of the beds is staggered so that, at any given time, one bed is in the first half of its adsorption mode, another bed is in the second half of its adsorption mode, and the third bed is in the desorption mode. Because one of the three beds is being desorbed at any given time, steam flow to the system is continuous.

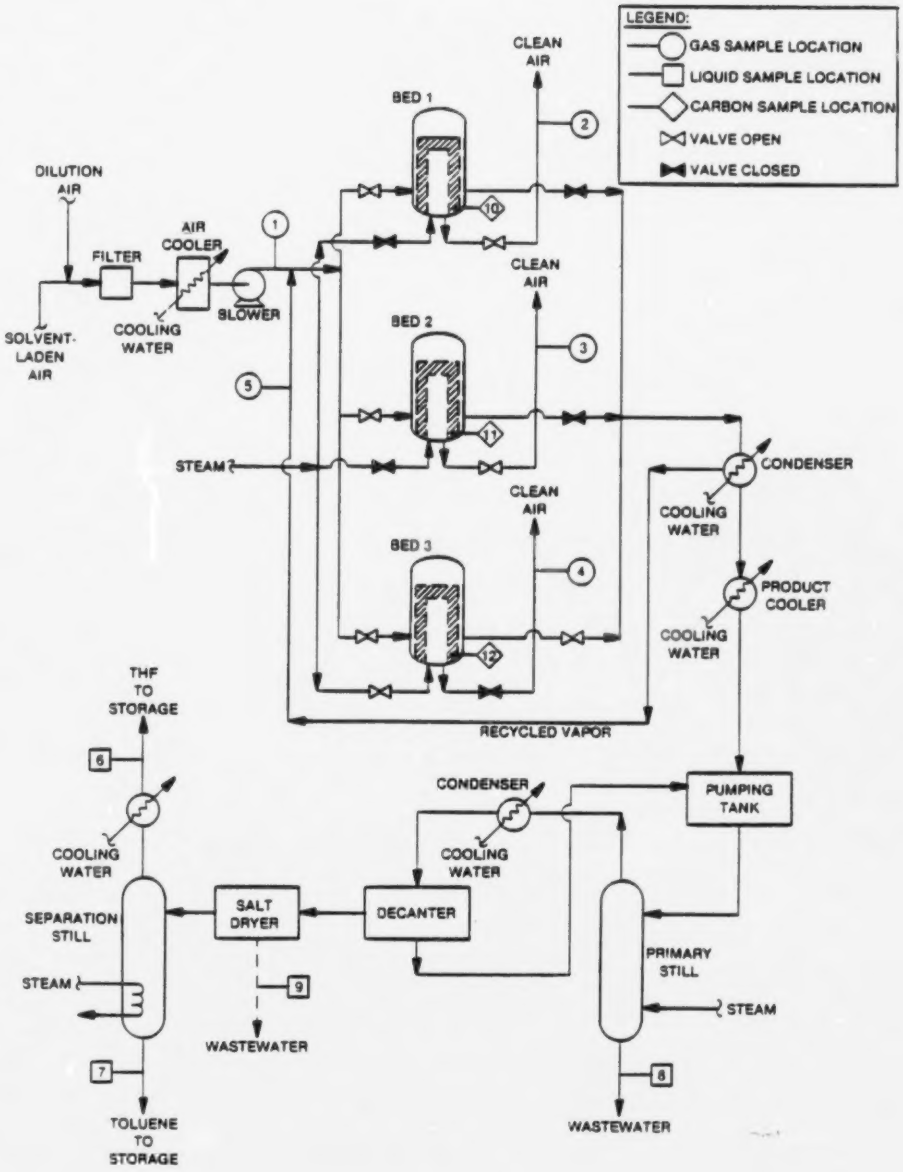
LEGEND:
GAS SAMPLE LOCATION
LIQUID SAMPLE LOCATION
CARBON SAMPLE LOCATION
VALVE OPEN
VALVE CLOSED
CLEAN AIR
BED 1
②
DILUTION AIR
FILTER
AIR COOLER
①
⑩
SOLVENT-LADEN AIR
COOLING WATER
BLOWER
CLEAN AIR
BED 2
③
⑤
⑪
STEAM
CONDENSER
COOLING WATER
CLEAN AIR
BED 3
④
PRODUCT COOLER
COOLING WATER
⑫
THF TO STORAGE
RECYCLED VAPOR
6
CONDENSER
PUMPING TANK
COOLING WATER
COOLING WATER
SEPARATION STILL
SALT DRYER
DECANTER
PRIMARY STILL
STEAM
9
STEAM
WASTEWATER
7
8
TOLUENE TO STORAGE
WASTEWATER

Figure 7-1. Plant 2 solvent recovery system.

During both test periods, a complete cycle required 96 minutes, as shown below:

Segment	Bed 1	Bed 2	Bed 3	Time
1	Ads	Ads	Des	32 min.
2	Ads	Des	Ads	32 min.
3	Des	Ads	Ads	32 min.
				96 min.

Plant 2 is instrumented as follows:

- a timer indicating the operating status of each bed;
- a single-column gas chromatograph (GC) for periodic batch sampling of the influent and effluent air streams;
- a turbine meter indicating steam flow to the beds;
- temperature indicating devices for inlet SLA temperature, bed temperatures, exhaust temperatures, and condenser process and cooling water temperatures; and,
- a control panel dedicated to operation and monitoring of the distillation section.

With the exception of the steam flow meter, all instrumentation was operational during the time of the testing.

TEST RESULTS

The performance of the Plant 2 carbon adsorption system was measured based upon characterization of the following: (1) general operating parameters; (2) VOC control performance; and (3) carbon, solvent, and wastewater properties. Results of the characterizations are presented in this section.

General Operating Parameters

General operating conditions for the Plant 2 carbon adsorption system during the original and repeat test periods are presented in Table 7-2. The data are categorized as adsorption and regeneration mode data.

The adsorption mode data for Plant 2 indicate several deviations from design conditions and/or between the original and repeat test periods. Significant deviations occurred with regard to solvent type, operating temperatures, and SLA throughput.

During the original test period in 1982, the system controlled solvent vapors from two coating lines, each of which used a 50/50 volume percent (design) mixture of the THF/toluene. During the repeat test period in 1983, the carbon adsorption system controlled solvent vapors from three coating lines, each using a 75/25 percent mixture of the THF/toluene (the change in formulation was made in response to changing coated product specifications). In general, the solvent with a higher percentage of THF tends to be adsorbed less efficiently by the carbon bed; the liquid molar volumes of THF and toluene are approximately 88 and 118 cm^3/mol, respectively.

Also, the system operated at higher inlet temperatures and lower inlet relative humidities during the repeat test period, due to warmer ambient temperatures and the addition of the third drying oven. For both test periods, however, the average inlet SLA temperature was at or below the design temperature of 32°C (90°F).

TABLE 7-2. GENERAL OPERATING DATA FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 2.

Operating Parameter	Operating Conditions[a]	
	Original Test - February, 1982	Repeat Test - December, 1983
Adsorption Mode		
Solvent type	50% THF/50% toluene	75% THF/25% toluene
Mode length	64 min	64 min
Inlet SLA flow rate	4.6 Nm^3/sec (9,800 scfm)	4.5 Nm^3/sec (9,500 scfm)
SLA superficial velocity	0.24 m/sec (47 ft/min)	0.23 m/sec (46 ft/min)
Bed residence time	0.9 sec	0.9 sec
SLA temperature drop across air cooler	9°C (17°F)	13°C (24°F)
Inlet SLA temperature (after air cooler)	23°C (74°F)	32°C (90°F)
Inlet SLA relative humidity	30%	17%
Carbon bed pressure drop	Bed 1 - 1.0 kPa (4.2 in. H_2O) Bed 2 - 1.0 kPa (4.0 in. H_2O) Bed 3 - 0.9 kPa (3.6 in. H_2O)	Bed 1 - 1.2 kPa (5.0 in. H_2O) Bed 2 - 1.1 kPa (4.6 in. H_2O) Bed 3 - 1.2 kPa (5.0 in. H_2O)
Outlet air flow rate	Bed 1 - 2.3 Nm^3/sec (4,900 scfm) Bed 2 - 2.6 Nm^3/sec (5,500 scfm) Bed 3 - 2.6 Nm^3/sec (5,500 scfm)	Bed 1 - 2.4 Nm^3/sec (5,000 scfm) Bed 2 - 2.7 Nm^3/sec (5,700 scfm) Bed 3 - 2.5 Nm^3/sec (5,400 scfm)
Outlet air temperature	36°C (96°F)	34°C (93°F)
Outlet air relative humidity	35%	20%
Regeneration Mode		
Desorption period length	32 min	32 min
Cooldown period length	NA[b]	NA[b]
Standby period length	NA[b]	NA[b]
Steam flow rate (continuous)	270 kg/hr (600 lb/hr)[c]	390 kg/hr (860 lb/hr)[d]
Steam/recovered solvent ratio	5.2 kg/kg (5.2 lb/lb)[e]	6.5 kg/kg (6.5 lb/lb)[f]
Steam pressure	390 kPa (42 psig)	280 kPa (26 psig)
Steam temperature	143°C (289°F)	132°C (269°F)
Wastewater flow rate	360 kg/hr (800 lb/hr)[c]	195 kg/hr (430 lb/hr)[g]

[a] Average values are presented.

[b] Not applicable to Plant 2.

[c] Based on plant estimates.

[d] Estimated from wastewater flow rate.

[e] Based on plant solvent recovery data and plant estimates of steam consumption.

[f] Based on measured VOC data and estimated steam flow rate.

[g] Measured data.

Finally, the processed SLA throughputs were similar for the two test periods, nominally 4.6 Nm^3/sec (9,700 scfm). However, this flow rate was about 25 percent lower than the design flow rate. As a result, the bed superficial velocity averaged a relatively conservative value of nominally 0.24 m/sec (47 ft/min).

The regeneration mode data for Plant 2 in Table 7-2 indicate different performance characteristics for the original and repeat test periods. Desorption mode length was constant at 32 minutes per bed, but steam temperature was higher during the original test period, by approximately 11°C (20°F). The data also indicate apparent differences in steam flow rate, steam/solvent ratio, and wastewater flow rate. However, these regeneration parameters were quantified during the original test program based upon plant estimates rather than actual measurements. During the repeat testing, wastewater flow rate, steam flow rate and steam/solvent ratio were projected, yielding data that are more representative of actual operation than those previously based on plant estimates. The estimated steam consumption rate of 390 kg/hr (860 lb/hr) compared closely with the design value of 410 kg/hr (900 lb/hr). The estimated steam/solvent ratio also approximated the design value, averaging 6.5 kg/kg (6.5 lb/lb).

VOC Control Efficiency Performance

Results of the VOC control efficiency testing conducted at Plant 2 are summarized in Table 7-3. During the original testing, with carbon that had been in service for two years, VOC control efficiency for all three beds exceeded 99 percent. Repeat testing with the same carbon almost two years later indicted VOC control efficiencies of 97, 93 and 96 percent for Beds 1, 2 and 3, respectively. (The VOC control efficiencies are expressed on a "system" basis; i.e., the recycle gas stream was considered to be an internal loop of the solvent recovery system.)

TABLE 7-3. VOC CONTROL EFFICIENCY DATA FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 2

Test	Inlet VOC Loading		Outlet VOC Emissions		VOC Control Efficiency,%[b,c]
	Concentration, ppmv[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	Concentration, ppmv[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	
Original Test - February, 1982					
Bed 1	1,320	40.0 (83.7)	5	0.15 (0.33)	99.6
Bed 2	1,520	43.6 (96.1)	2	0.071 (0.16)	99.8
Bed 3	1,580	51.1 (112.5)	2	0.078 (0.17)	99.8
Repeat Test - December, 1983					
Bed 1	905	25.4 (55.9)	23	0.68 (1.49)	97.3
Bed 2	1,170	32.8 (72.3)	72	2.40 (5.29)	92.7
Bed 3	1,330	37.2 (82.0)	48	1.54 (3.39)	95.9

[a] As a 50/50 volume percent mixture of THF and toluene.

[b] Average values are presented.

[c] Efficiency expressed on a "system" basis.

The following factors apparently contributed to the degradation in VOC control performance:

- increased carbon age (lower activity);
- lower regeneration steam temperature;
- higher inlet SLA temperatures; and
- the use of a greater percentage of THF in the solvent formulation.

Despite the addition of a third coating line to the process prior to the repeat testing, inlet solvent concentration were similar during the two test periods. This phenomenon was due to the production schedule during the week of the repeat test; only on rare occasions were all coating lines in operation simultaneously. The similarity in inlet solvent concentration for the two test periods precluded it as a variable contributing to the difference in VOC control performance.

The example VOC concentration profiles shown for Bed 2 in Figure 7-2 demonstrate the difference in VOC control performance for the original and repeat test periods. For essentially equivalent average inlet solvent loading levels of about 1,200 ppmv, markedly different outlet VOC concentration profiles are evident for the two sets of data. The original outlet VOC data, represented by the dashed line, showed an initial brief concentration spike as the relatively hot, moisture-laden bed was placed into adsorption service. Thereafter, the outlet concentration decreased to a steady level averaging 1 ppmv (note the expanded vertical scale). Solvent breakthrough was not apparent.

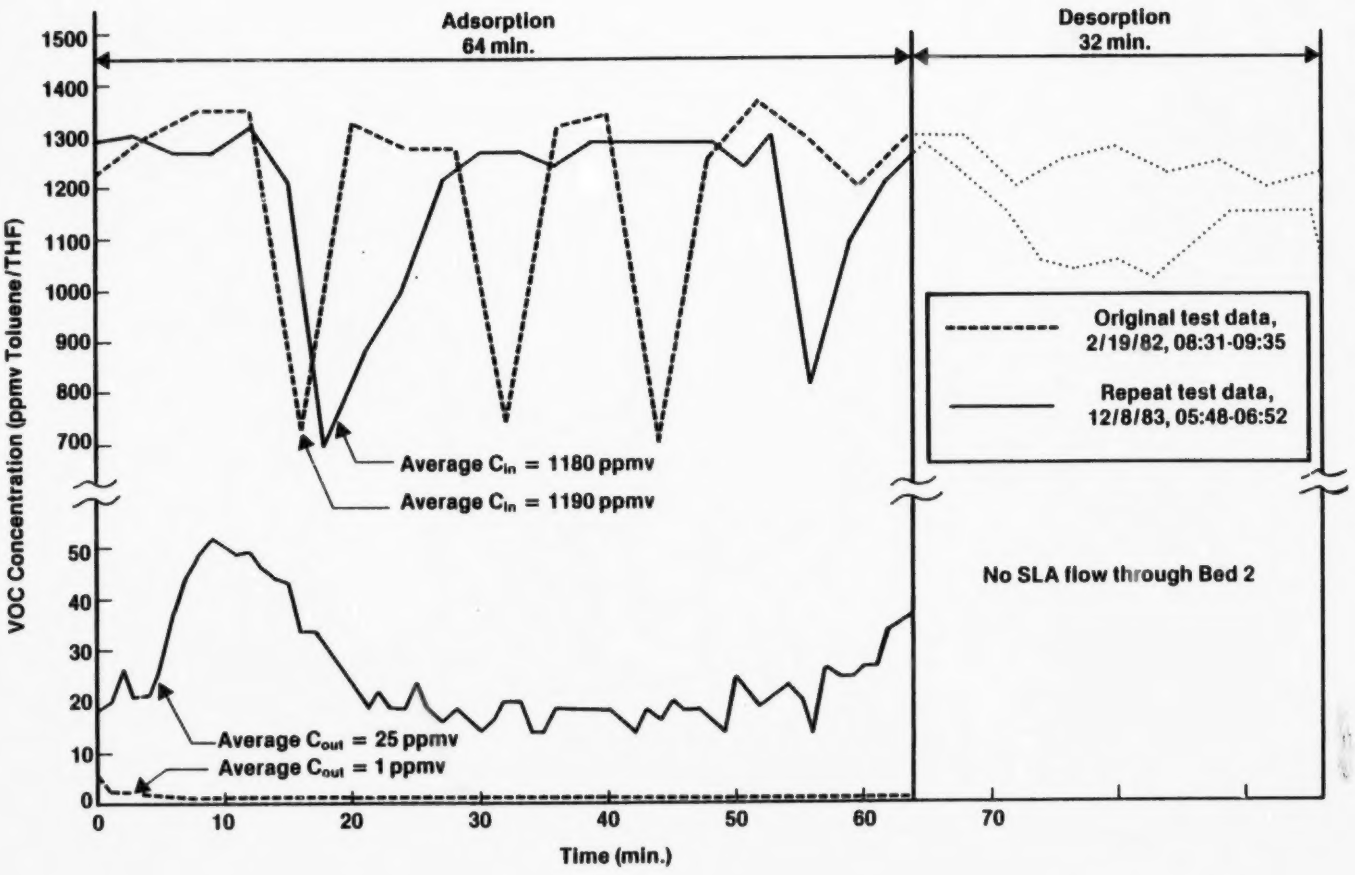

Figure 7-2. Plant 2 VOC concentration profiles - Bed 2.

The outlet VOC data measured during the repeat test period, shown by the solid line, showed an exaggerated spike early in the cycle and a steady breakthrough trend in the latter half of the cycle. The average VOC concentration over this adsorption cycle was 25 ppmv.

Periodic GC analysis of the inlet SLA indicated THF and toluene fractions consistent with the plant's reported coating solvent formulation. Also, GC analysis of the adsorber exhaust air VOCs showed that THF was the only solvent component present; i.e., the toluene fraction was preferentially adsorbed and tended to partition from the THF during adsorption. This result is consistent with the higher liquid molar volume of toluene.

Carbon, Solvent and Wastewater Characteristics

Characteristics of the carbon, solvent and wastewater from the Plant 2 solvent recovery system are summarized in Table 7-4 and discussed below.

Analysis of the coconut shell-based bed carbon indicated possible degradation in adsorption capacity relative to virgin carbon levels. This result is apparent from a combination of the CCl_4 activity values and the volatiles content data. However, these same parameters indicate that bed carbon adsorption capacity was relatively constant for the original and repeat test periods, despite the difference in carbon service life (2.0 years vs 3.8 years). The carbon particle sizing data show that the bed carbon consisted of a greater proportion of fines than the virgin carbon, due to attrition.

The solvent analysis data indicate that the distillation section of the Plant 2 solvent recovery unit yielded THF of approximately 95 percent purity and toluene of approximately 90 percent purity. The recovered THF fraction was contaminated with water at levels approximating 2 percent.

TABLE 7-4. CHARACTERISTICS OF CARBON, SOLVENT, AND WASTEWATER FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 2

Parameter	Original Test Period February, 1982[a]				Repeat Test Period December, 1983[a]		
Carbon Analysis[b]	Bed 1[c]	Bed 2[c]	Bed 3[c]	Virgin	Bed 1[c]	Bed 2[c]	Bed 3[c]
Service life	2.0 yr	2.0 yr	2.0 yr	NA	3.8 yr	3.8 yr	3.8 yr
CCl_4 activity, %	33	20	18	48	29	22	22
CCl_4 retentivity, %	20	12	7	33	16	9	9
Volatiles, %	11	16	<1[d]	3	10	16	12
Surface area, m^2/g	NM	NM	NM	761	NM	NM	NM
Moisture, %	15	12	10	7	3	2	10
Particle size, mm[e]	1.7	1.7	1.7	1.9	1.6	NM	NM
Solvent Analysis	Recovered THF		Recovered Toluene		Recovered THF		Recovered Toluene
THF, wt %	97.9		10.2		93.5		11.6
Toluene, wt %	0.5		89.8		4.1		88.1
Other, ppm (wt)[f]	NM		NM		0.2		0.3
Water, wt %	1.6		<0.1		2.2		<0.1
Wastewater Analysis							
THF, ppm (wt)		260				5	
Toluene, ppm (wt)		710				76	
Other, ppm (wt)		1,000				76	

NA = Not applicable NM = Not measured

[a] Average values are presented.

[b] Carbon samples were collected after bed desorption.

[c] Carbon samples from various locations in the annular bed could not be obtained. The bed samples were collected from a drain near the bottom of the three beds and were assumed to represent "average" carbon.

[d] Suspect data.

[e] Sieve size through which 50% of the carbon sample weight passed.

[f] As hexane.

The average wastewater analysis results for the two test periods suggest that significant differences in distillation performance were measured; organic contents of the wastewater during the original and repeat test periods averaged about 2,000 and 200 ppm, respectively. However, the differences were probably due to analysis of a limited number of samples (the organic concentration of individual samples ranged over several orders of magnitude). For both test periods, the average organic content of the wastewater represented less than 0.2 percent of the total solvent processed by the solvent recovery system.

COST DATA

Cost data for the Plant 2 solvent recovery system are presented in this section. Information presented includes a list of equipment, capital costs, and annualized costs.

Equipment List for Costing

The following major equipment items are included within the cost data supplied for the Plant 2 solvent recovery system:

- SLA transport equipment, including the SLA blower and ductwork from the ovens;
- SLA preconditioning equipment, including the filter and air cooler;
- solvent adsorption equipment, consisting of the adsorber vessels and related equipment;
- solvent separation equipment, consisting of the distillation section of the solvent recovery unit; and
- solvent storage equipment, including the THF and toluene storage tanks and piping.

Specifically excluded from the cost data are equipment items associated with solvent/coating blending, surface coating and web drying (ovens).

Capital Costs

Capital costs for the Plant 2 solvent recovery system are listed in Table 7-5. Costs are expressed in late 1983 dollars. As shown, the total estimated capital cost is $650,000, which corresponds to a unit cost of $108,000/Nm^3/sec ($51/scfm), relative to the design SLA processing capacity.

Annualized Costs

Annualized costs for the Plant 2 system, in 1983 dollars, are presented in Table 7-6. As shown, annualized costs total approximately $325,000 per year, with capital recovery, steam, and labor costs representing the largest cost components. On a unit basis, annualized costs total $0.61/kg ($0.28/lb) of recovered solvent.

TABLE 7-5. CAPITAL COSTS FOR THE SOLVENT RECOVERY SYSTEM AT MAGNETIC TAPE PLANT 2[a]

DIRECT COSTS	
• Delivered equipment	$ 441,000
• Installation materials (ducting, piping foundations, buildings, electrical, instrumentation, insulation, painting, tankage, etc.)	127,000
• Installation labor	Included above
TOTAL DIRECT COSTS (TDC)	$ 568,000
INDIRECT COSTS	
• Engineering and supervision	$ 28,000[b]
• Miscellaneous construction expenses	0[b]
• Contractor's fees	0[b]
• Contingencies	23,000[b]
TOTAL INDIRECT COSTS (TIC)	$ 51,000[b]
OTHER COSTS	
• Interest during construction	$ 0[b]
• Startup	31,000[b]
• Other	0[b]
TOTAL OTHER COSTS (TOC)	$ 31,000
TOTAL CAPITAL COSTS (TCC = TDC + TIC + TOC)	$ 650,000
RELATIVE CAPITAL COSTS	
• TCC/design SLA flow rate	\$ 108,000/Nm^3/sec (\$51/scfm)
• TCC/design carbon charge	\$ 192/kg (\$87/lb)

[a] All cost figures, unless otherwise noted, were obtained by scaling plant-supplied data to a late 1983 capital cost basis. Scaling factors were obtained from the Chemical Engineering Plant Cost Index; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

TABLE 7-6. ANNUALIZED COSTS FOR THE SOLVENT RECOVERY SYSTEM AT MAGNETIC TAPE PLANT 2[a]

DIRECT COSTS	
• Labor	
--operating	$ 30,000[b]
--maintenance	8,000[b]
--laboratory	0[b]
--supervisory	10,000[b]
• Maintenance materials	6,000[b]
• Activated carbon	2,000[b]
• Utilities	
--electricity	30,000
--steam	60,000
--cooling water	16,000[b]
--chilled water	0
TOTAL DIRECT COSTS (TDC)	$ 160,000/yr
INDIRECT COSTS	
• Capital recovery[c]	$ 106,000[b]
• Labor and plant overhead	37,000[b]
• General and administrative	6,000[b]
• Insurance and property tax	15,000[b]
TOTAL INDIRECT COSTS (TIC)	$ 164,000/yr
TOTAL ANNUALIZED COSTS (TAC = TDC + TIC)	$ 325,000/yr
RELATIVE ANNUALIZED COSTS	
• TAC/actual annual SLA throughput	$ 3.3/10^3Nm^3 (\$0.09/10^3 scf)[d]
• TAC/actual annual solvent recovery	$ 0.61/kg (\$0.28/lb)[d]

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[a] All cost figures, unless otherwise noted, were obtained by multiplying plant-supplied unit costs (e.g., $/man-hour) by measured or plant-supplied operating rates (e.g., man-hours/week). Costs are expressed on a late 1983 basis; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

[c] Capital recovery = TCC x $\frac{(1+i)^n i}{(1+i)^n - 1}$

where TCC = total capital cost
i = interest rate @ 0.10
n = equipment life @ 10 years

[d] Based upon original test data.

SECTION 8

TEST RESULTS - PLANT 3

The carbon adsorption system at Plant 3, a magnetic tape manufacturing facility, was tested in March 1982. Design specifications and a process description for the Plant 3 system are presented in this section, followed by results of the performance testing. Capital and annualized cost data are also presented.

DESIGN SPECIFICATIONS AND PROCESS DESCRIPTION

Plant 3 operates two magnetic tape coating lines in a manner similar to Plant 2. The key difference from a solvent recovery standpoint is the Plant 3 solvent formulation, which primarily consists of toluene and THF with small amounts of methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK) and cyclohexanone.

The five-component solvent mixture is recovered in a system featuring three pairs of annular carbon beds and a batch distillation unit. Design specifications for the carbon adsorption system are presented in Table 8-1. As shown, the six-bed Aircon design was started up in 1974 and is sized to handle a 10.9 Nm^3/sec (23,000 scfm) SLA stream. Also, the system is designed to process a solvent formulation of THF, toluene, MEK, MIBK and cyclohexanone at a total inlet concentration of 2,000 ppmv (as a 50/50 volume percent mixture of THF and toluene, the primary components).

A process flow diagram of the solvent recovery system at Plant 3 is shown in Figure 8-1. The initial step in the process involves separation of the SLA stream into two flows that are filtered and cooled prior to introduction to

TABLE 8-1. DESIGN SPECIFICATIONS FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 3

Design Parameter	Design Specification
MANUFACTURER	Aircon
STARTUP DATE	1974
CARBON BED SPECIFICATIONS	
Configuration	annular (vertical)
Number of beds	6[a]
Dimensions	
• outer diameter	2.1 m (6.9 ft)
• inner diameter	1.6 m (5.4 ft)
• thickness	23 cm (9 in)
• weight	1.8 m (6 ft)
Carbon loading per bed	2,950 kg (6,500 lb)
Carbon type	Union Carbide JXC
Carbon base	acid sludge coke
SLA SPECIFICATIONS	
Flow direction through beds	outward
Flow rate to carbon beds	10.9 Nm^3/sec (23,000 scfm)
Relative flow rate[b]	0.0012 Nm^3/sec - kg carbon (1.1 scfm/lb carbon)
Superficial bed velocity	0.36 m/sec (70 ft/min)
Residence time in bed	0.6 sec
Inlet temperature	29°C (85°F)
SOLVENT SPECIFICATIONS	
Type	THF/toluene/MEK/MIBK/cyclohexanone
Inlet mass loading	270 kg/hr (600 lb/hr)
Inlet concentration loading	2,000 ppmv
Relative inlet mass loading[b]	0.031 kg/kg carbon/hr (0.031 lb/lb carbon/hr)
REGENERATION SPECIFICATIONS	
Steam consumption	1,090 kg/hr (2,400 lb/hr)[c]
Steam/recovered solvent	NA[d]
Cooling/drying medium	ambient air
SOLVENT REMOVAL EFFICIENCY	NS[e]
MATERIALS OF CONSTRUCTION	
Adsorbers	carbon and stainless steel
Ductwork	carbon steel
Piping	carbon steel
METHOD OF SOLVENT SEPARATION	distillation

[a] Only 4 of the 6 beds were in operation during the test period (2 were on permanent standby).

[b] Refers to the solvent and SLA loading to the carbon in the on-line (adsorbing) carbon beds.

[c] Per desorption.

[d] Data not available due to unspecified frequency of desorption.

[e] None specified.

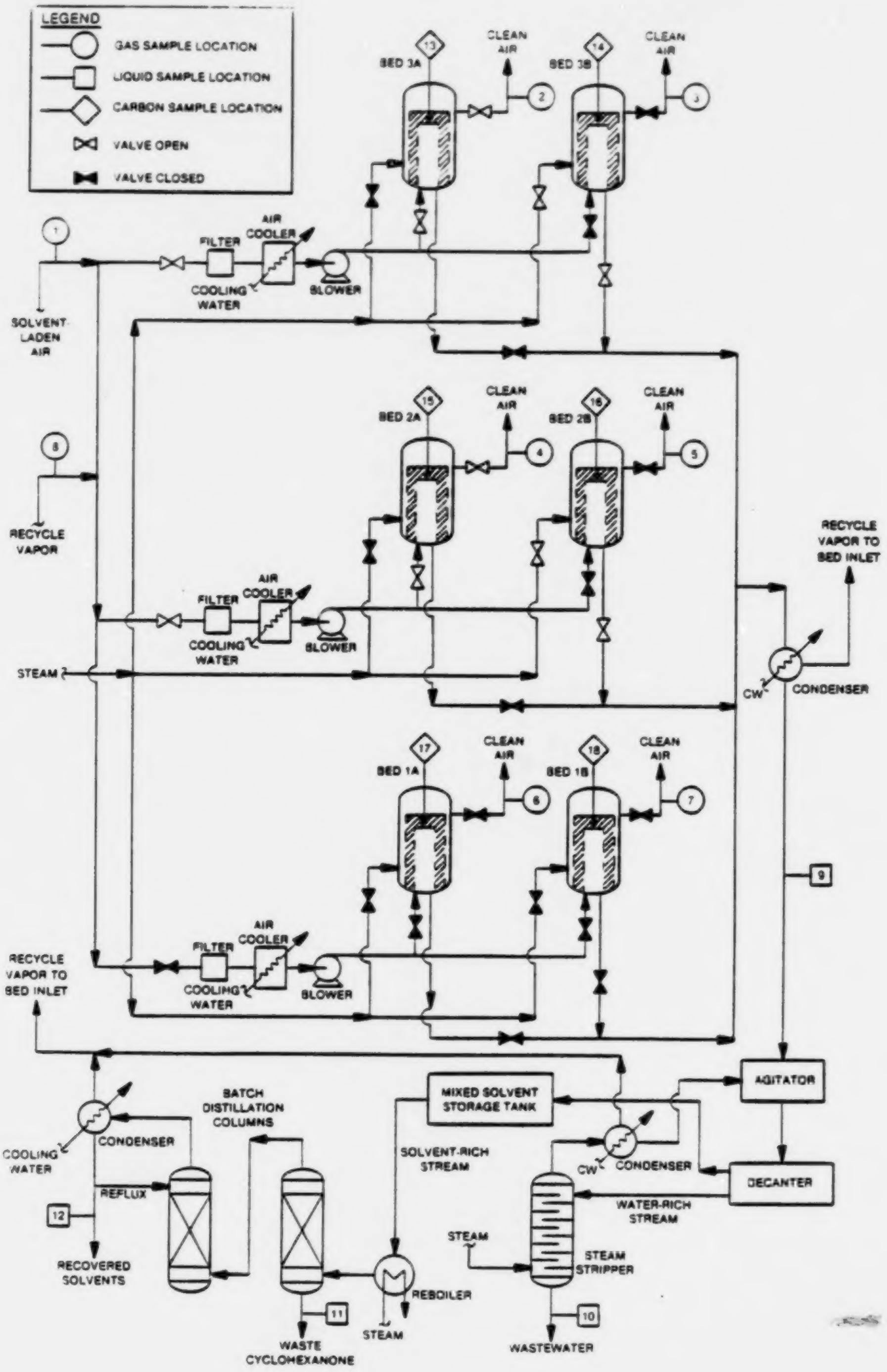
LEGEND
GAS SAMPLE LOCATION
LIQUID SAMPLE LOCATION
CARBON SAMPLE LOCATION
VALVE OPEN
VALVE CLOSED
13
14
BED 3A
BED 3B
CLEAN AIR
CLEAN AIR
2
3
1
SOLVENT-LADEN AIR
FILTER
AIR COOLER
COOLING WATER
BLOWER
15
16
BED 2A
BED 2B
CLEAN AIR
CLEAN AIR
4
5
8
RECYCLE VAPOR
FILTER
AIR COOLER
COOLING WATER
BLOWER
STEAM
RECYCLE VAPOR TO BED INLET
CW
CONDENSER
17
18
BED 1A
BED 1B
CLEAN AIR
CLEAN AIR
6
7
9
FILTER
AIR COOLER
COOLING WATER
BLOWER
RECYCLE VAPOR TO BED INLET
AGITATOR
MIXED SOLVENT STORAGE TANK
BATCH DISTILLATION COLUMNS
CONDENSER
COOLING WATER
REFLUX
12
RECOVERED SOLVENTS
SOLVENT-RICH STREAM
CW
CONDENSER
DECANTER
WATER-RICH STREAM
STEAM
STEAM STRIPPER
REBOILER
STEAM
11
WASTE CYCLOHEXANONE
10
WASTEWATER

Figure 8-1. Plant 3 solvent recovery system.

two parallel carbon bed trains. (During the test period, only two carbon bed pairs were in service at any given time; the third pair was on permanent standby as a spare module.) In each on-line train, the SLA enters the interior section of the adsorbing annular carbon bed (the other bed of the pair is in the regeneration mode). The SLA flows outward through the annular bed and is stripped of solvent content. The treated air is exhausted to the atmosphere from the exterior of the annulus through separate stacks.

When an on-line carbon bed completes its adsorpton mode, the vessel is closed off to SLA flow, and low-pressure steam is introduced to the exterior of the annulus. The steam passes inward through the bed, desorbing the solvent from the bed. The steam/solvent vapor is condensed, with uncondensed vapors and inerts recycled to the inlet of the system. The condensed solvent and water vapors are then separated into component fractions in the batch distillation unit. The recovered solvents are sent to storage for reuse in the coating process. The wastewater phase is discharged to the sewer system.

Following steam desorption, the carbon bed is cooled with ambient air. A single fan (not shown in Figure 8-1) cools each of the two regenerating carbon beds in succession. Following the cooldown period, the regenerated bed is placed into the standby mode.

The sequencing of the adsorption/regeneration modes of the beds is controlled by a timer. The complete cycle can be divided into the following segments:

Segment	Bed 1A	Bed 1B	Bed 2A	Bed 2B	Time
1	Ads	Des	Des	Ads	23 min.
2	Ads	Des	Cool	Ads	8 min.
3	Ads	Des	Std	Ads	4 min.
4	Ads	Cool	Ads	Des	8 min.
5	Ads	Std	Ads	Des	4 min
6	Des	Ads	Des	Ads	23 min.
7	Des	Ads	Ads	Cool	8 min.
8	Des	Ads	Ads	Std	4 min.
9	Cool	Ads	Des	Ads	8 min.
10	Std	Ads	Des	Ads	4 min.

As shown, the total cycle time during the original test period in 1982 was 94 minutes. (The above data, while presented for the Bed 1/Bed 2 pairs, also applied to other combinations of on-line bed pairs; i.e., Bed 2/Bed 3 and Bed 1/ Bed 3.)

The solvent recovery system at Plant 3 is instrumented as follows:

- a control panel indicating each bed's operating status;
- temperature, pressure and liquid level indicators at appropriate places in the system;
- a gas chromatograph for weekly analysis of effluent concentrations; and,
- a control panel for the distillation unit.

All process instrumentation was operational during the original test period.

TEST RESULTS

Testing of the Plant 3 carbon adsorption system focused on the characterization of: (1) general operating parameters; (2) VOC control performance; and (3) carbon, solvent and wastewater properties. Results of these characterizations are presented in this section.

General Operating Parameters

General operating data for the Plant 3 system as measured during the original test period are presented in Table 8-2. The data are categorized as adsorption and regeneration mode data.

TABLE 8-2. GENERAL OPERATING DATA FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 3

Operating Parameter	Operating Conditions[a] Original Test - March, 1982
Adsorption Mode	
Solvent type	THF/toluene/MEK/MIBK/cyclohexanone
Mode length	47 min
Inlet SLA flow rate	9.34 Nm^3/sec (19,800 scfm)
SLA superficial velocity	0.45 m/sec (90 ft/min)
Bed residence time	0.5 sec
SLA temperature drop across air cooler	11°C (20°F)
Inlet SLA temperature (after air cooler)	27°C (81°F)
Inlet SLA relative humidity	30%
Carbon bed pressure drop	Beds 1A/1B - 1.4 kPa (5.8 in. H_2O) Beds 2A/2B - 1.3 kPa (5.4 in. H_2O) Beds 3A/3B - 0.97 kPa (3.9 in. H_2O)
Outlet air flow rate	Bed 1A - 4.8 Nm^3/sec (10,100 scfm)[b] Bed 1B - 4.8 Nm^3/sec (10,200 scfm)[b] Bed 2A - 4.8 Nm^3/sec (10,100 scfm) Bed 2B - 4.8 Nm^3/sec (10,200 scfm) Bed 3A - 4.1 Nm^3/sec (8,670 scfm) Bed 3B - 4.2 Nm^3/sec (8,950 scfm)
Outlet air temperature	26°C (78°F)
Outlet air relative humidity	58%
Regeneration Mode	
Desorption period length	35 min
Cooldown period length	8 min
Standby period length	4 min
Steam flow rate (per bed desorption)	1,320 kg/hr (2,900 lb/hr)[c]
Steam/recovered solvent ratio	6.0 kg/kg (6.0 lb/lb)
Steam pressure	288 kPa (27 psig)
Steam temperature	132°C (270°F)
Wastewater flow rate	1,720 kg/hr (3,790 lb/hr)[d]

[a] Average values are presented.

[b] Outlet air flow rates from Beds 1A and 1B were not measurable due to stack configuration. The flow rates were estimated to equal those of Beds 2A and 2B due to similar bed pressure drops.

[c] Estimated from plant data.

[d] Includes condensed desorption steam and condensed stripper steam (per plant data).

The adsorption mode data for Plant 3 indicate that the processed SLA throughput, 9.37 Nm^3/sec (19,800 scfm), was lower than the design value by almost 15 percent. However, only two of the three carbon bed pairs were in service, so the superficial bed velocity was actually higher than the design value, averaging 0.45 m/sec (90 ft/min). The test data indicated that air flow rate through bed pairs 1 and 2 was greater than through bed pair 3. The flow rate differences were apparently caused by physical factors such as header duct configuration, differences in carbon bed depth or carbon particle size, etc.

The regeneration mode data show that the steam flow rate data averaged 1,320 kg/hr (2,900 lb/hr), which is approximately 20 percent greater than the design amount. As a result, the steam/recovered solvent ratio was relatively high, averaging 6.0 kg/kg (6.0 lb/lb).

VOC Control Efficiency Performance

Summarized VOC control efficiency data for the Plant 3 carbon adsorption system are presented in Table 8-3. As shown, the six beds achieved VOC control efficiencies ranging from 92 to 97 percent. Average inlet VOC concentrations averaged approximately 3,000 ppmv.

The highest VOC control efficiencies were measured for Beds 3A and 3B, apparently as a result of two factors. First, Beds 3A and 3B contained fresher carbon charges (two weeks' service vs. five months' service for bed pairs 1 and 2). Also, Beds 3A and 3B were subjected to lower inlet VOC loadings than bed pairs 1 and 2 due to the physical location of the VOC recycle line, as shown in Figure 8-1. (Inlet concentrations for all beds were measured upstream of the location at which the recycle gases were introduced to the SLA; i.e., the inlet concentrations reflect solvent loadings from the ovens.) Due to the physical configuration of the recycle stream, actual solvent loadings to bed pairs 1 and 2 were higher than those represented by the

TABLE 8-3. VOC CONTROL EFFICIENCY DATA FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 3

Test	Inlet VOC Loading		Outlet VOC Emissions		VOC Control Efficiency,%[b]
	Concentration, ppmv[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	Concentration, ppmv[a,b,c]	Mass Rate, kg/hr (lb/hr)[a,b,c]	
Original Test - March, 1982					
Bed 1A	2,300	148 (326)	158[d]	8.9 (19.6)[d]	94.0[e]
Bed 1B	2,440	153 (337)	170[d]	9.5 (20.9)[d]	93.8[e]
Bed 2A	3,970	245 (540)	352[d]	19.2 (42.3)[d]	92.2[e]
Bed 2B	3,470	212 (467)	190[d]	10.8 (23.8)[d]	94.9[e]
Bed 3A	3,720	199 (438)	134	6.6 (14.5)	96.7[f]
Bed 3B	3,420	184 (405)	108	5.7 (12.6)	96.9[f]

[a] As a 50/50 mole percent mixture of THF and toluene.

[b] Average values are presented.

[c] Includes solvent losses during cooling period.

[d] Includes solvent losses due to loading of bed by recycled VOCs.

[e] Efficiency expressed on a "system" basis.

[f] Efficiency expressed on a "bed" basis.

inlet SLA concentrations which is used to evaluate the VOC reduction efficiency of the bed. By comparison, bed pair 3 processed only inlet SLA solvent concentrations. Therefore, the higher loadings for bed pairs 1 and 2 caused a lower removal efficiency for the solvent vapors in the inlet SLA in comparison to the bed pair 3.

Comparative bed performance are shown in Figures 8-2 and 8-3. Figure 8-2 shows example VOC concentration profiles for Beds 1A and 1B. For both beds, the most significant losses occurred at the beginning of the adsorption and cooldown periods. As the bed cooled to normal operating temperatures, the outlet concentrations approximated 100 ppmv. The VOC concentration profiles shown for Beds 3A and 3B in Figure 8-3 show similar trends but at significantly reduced levels; initial solvent losses were considerably lower and baseline solvent emission concentrations were less than 50 ppmv. The difference in performance was apparently caused by the two factors described above, but the primary factor appeared to be differences in carbon life (activity), as discussed in the next section.

Carbon, Solvent and Wastewater Characteristics

Results of the carbon, solvent and wstewater analyses for the Plant 3 solvent recovery system are summarized in Table 8-4 and discussed below.

As shown, the characteristics of the acid sludge coke-based carbon used at Plant 3 varied with the sampling location and the bed. However, the adsorption properties of the carbon in each bed were proportional to the VOC control efficiency of the bed. For example, carbon from the influent side of Bed 3A (service life of 0.1 year) had a CCl_4 activity of 63 percent. Influent carbon from Beds 1A and 2A (service life of 0.4 year) had activities of 32 and 16 percent, respectively. By comparison, the VOC control efficiencies of Beds 3A, 1A and 2A averaged 96.7, 94.0 and 92.2 percent, respectively.

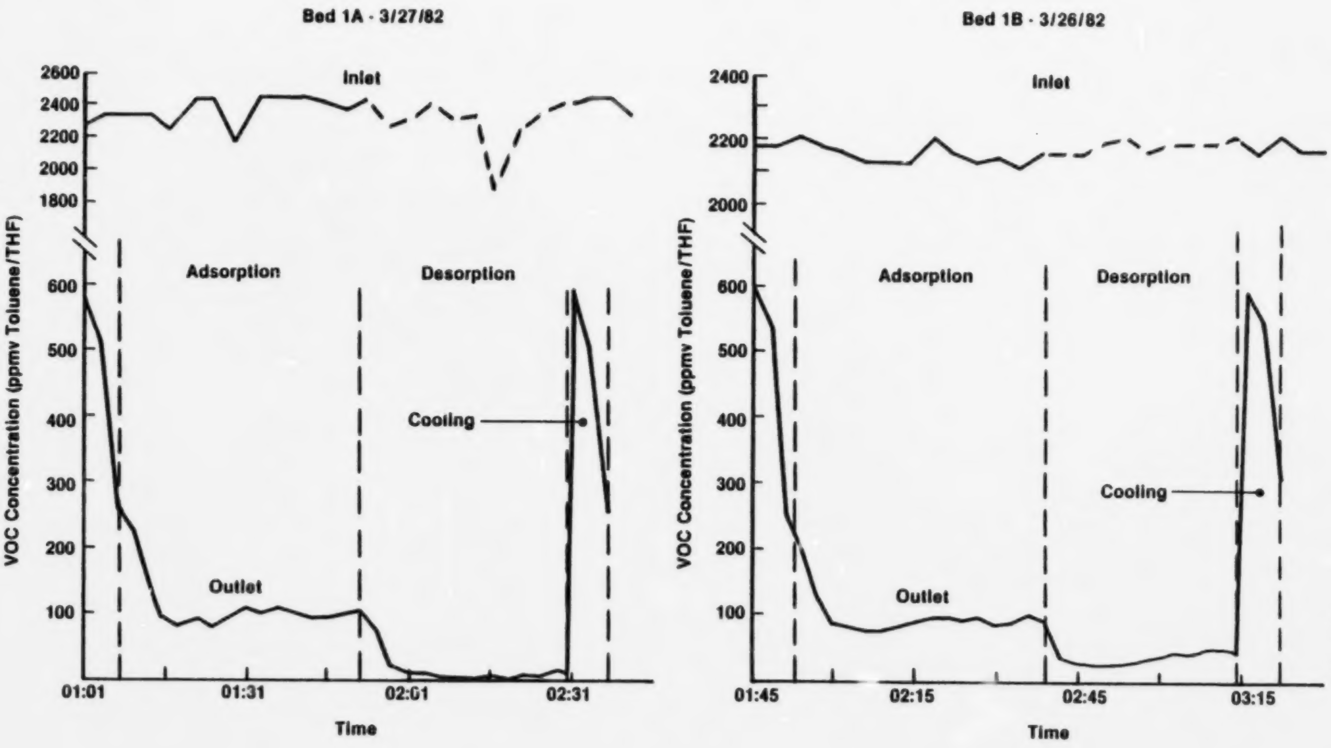

Figure 8-2. Plant 3 VOC concentration profiles - Beds 1A/B.

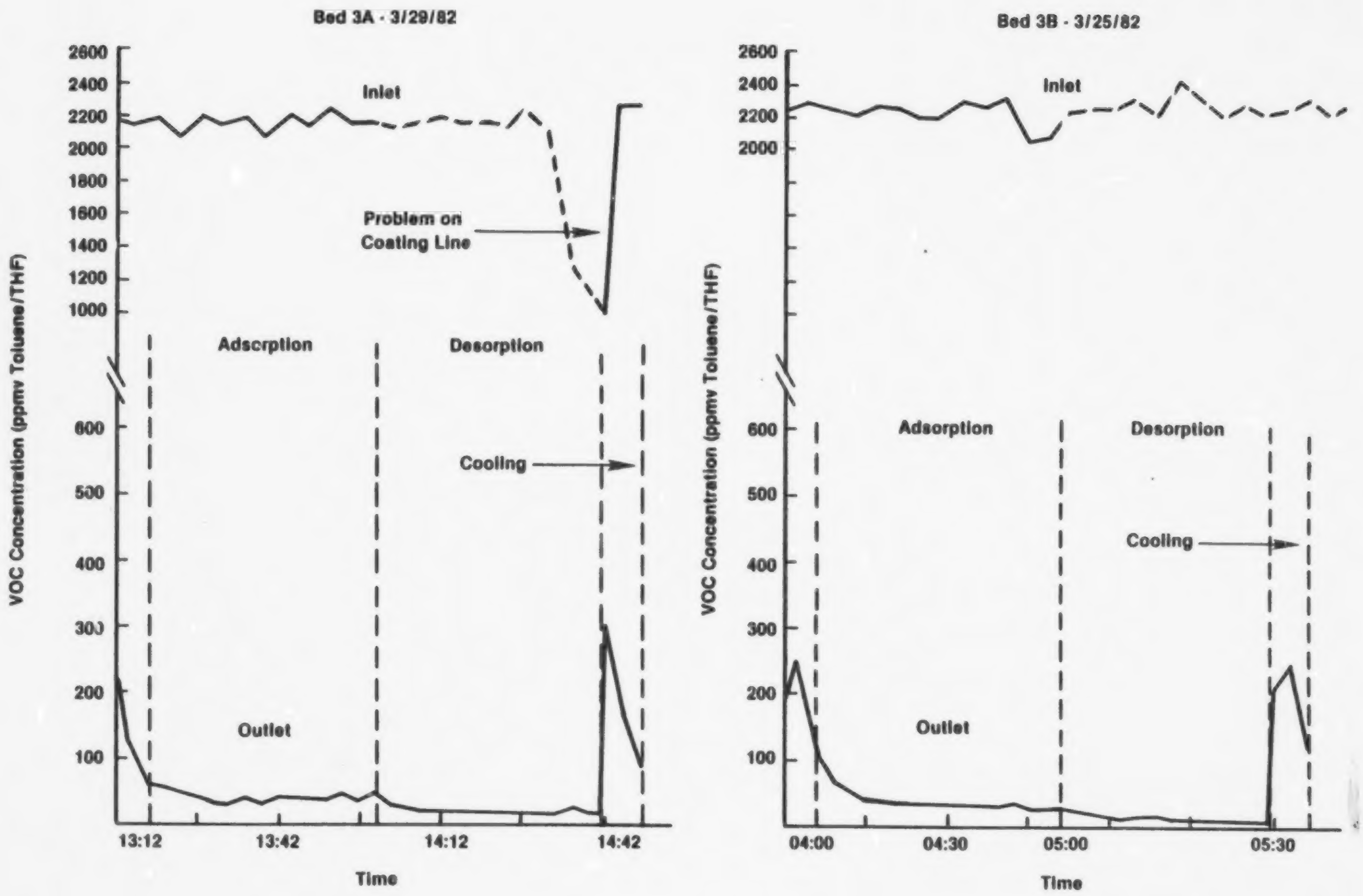

Figure 8-3. Plant 3 VOC concentration profiles - Beds 3A/B.

TABLE 8-4. CHARACTERISTICS OF CARBON, SOLVENT, AND WASTEWATER FOR THE CARBON ADSORPTION SYSTEM AT MAGNETIC TAPE PLANT 3

Parameter	Original Test Period - March, 1982[a]					
Carbon Analysis[b]	Bed 1A		Bed 2A	Bed 2B	Bed 3A	Virgin
	Influent	Effluent	Influent	Influent	Influent	
Service life	0.4 yr	0.4 yr	0.4 yr	0.4 yr	0.1 yr	NA
CCl_4 activity, %	32	33	16	26	63	69
CCl_4 retentivity, %	22	18	8	17	39	44
Volatiles, %	29	13	NM	NM	NM	1
Surface area, m^2/g	NM	NM	NM	NM	NM	902
Moisture, %	6	6	3	NM	7	2
Particle size, mm[c]	4.2	4.2	4.1	NM	4.2	4.2
Solvent Analysis	Feed THF	Recovered THF		Feed Toluene	Recovered Toluene	
Toluene, wt %	0.0	0.0		85.6	90.6	
THF, wt %	92.5	97.7		0.6	1.1	
MEK, wt %	7.0	2.3		1.4	1.0	
MIBK, wt %	0.0	0.0		7.8	7.0	
Cyclohexanone, wt %	0.0	0.0		4.5	0.2	
Water, wt %	0.5	NM		0.1	NM	
Wastewater Analysis						
Toluene, ppm (wt)			0			
THF, ppm (wt)			0			
MEK, ppm (wt)			330			
MIBK, ppm (wt)			0			
Cyclohexanone, ppm (wt)			0			
Other, ppm (wt)[d]			100			

NA = Not applicable NM = Not measured

[a] Average values are presented.

[b] Carbon samples were collected after bed desorption.

[c] Sieve size through which 50% of the carbon sample weight passed.

[d] As hexane.

The results of the particle size testing showed no significant difference in carbon size distribution. All tested virgin and bed carbon samples indicated similar size fractions.

Analysis of feed and recovered solvent samples indicated similar compositions. The recovered solvent mixture had a hydrocarbon content of nominally 45 percent toluene, 39 percent THF, 9 percent cyclohexanone, 4 percent MEK, and 3 percent MIBK. Separation of the recovered solvent into individual components faulted in "single" component solvent fractions having purity levels of approximately 90 percent (with the remaining 10 percent a combination of the other solvent fractions).

Analysis of wastewater from the system showed total organic concentrations of less than 500 ppm by weight, with MIBK being the only known solvent detected. Based on the wastewater flow rate presented in Table 8-2, the measured wastewater organic content represented less than 0.5 percent of the total solvent entering the solvent recovery system.

COST DATA

Cost data for the Plant 3 solvent recovery system are presented in this section. Included in the discussion is a listing of the equipment represented by the cost data, estimated capital costs and estimated annualized costs.

Equipment List for Costing

The following major equipment items are included within the cost data supplied for the Plant 3 solvent recovery system:

- SLA transport equipment, including blowers and ductwork from the oven;
- SLA preconditioning equipment, including the filters and air coolers;

- solvent adsorption equipment, consisting of the adsorber vessels and related equipment; and

- solvent separation equipment, consisting of the distillation section of the solvent recovery unit.

Specifically excluded from the cost data are equipment items associated with solvent/coating blending, surface coating, solvent drying systems (ovens), and solvent storage.

Capital Costs

Capital costs for the Plant 3 solvent recovery system are presented in Table 8-5. Capital costs are expressed in late 1983 dollars and total approximately \$1,880,000. On a unit basis, the total capital costs correspond to \$173,000 Nm^3/sec (\$82/scfm), relative to the design SLA throughput.

Annualized Costs

Annualized costs for the Plant 3 system, in 1983 dollars, are presented in Table 8-6. As shown, total annualized costs approximate \$1,430,000 per year, with steam, capital recovery and cooling water representing the major annualized cost components. The total annualized cost corresponds to a unit cost of \$0.66/kg (\$0.30/lb) of recovered solvent.

TABLE 8-5. CAPITAL COSTS FOR THE SOLVENT RECOVERY SYSTEM AT MAGNETIC TAPE PLANT 3[a]

DIRECT COSTS	
• Delivered equipment	$ NA[b]
• Installation materials (ducting, piping, foundations, buildings, electrical, instrumentation, insulation, painting, tankage, etc.)	NA[b]
• Installation labor	NA[b]
TOTAL DIRECT COSTS (TDC)	$ NA[b]
INDIRECT COSTS	
• Engineering and supervision	$ NA[b]
• Miscellaneous construction expenses	NA[b]
• Contractor's fees	NA[b]
• Contingencies	NA[b]
TOTAL INDIRECT COSTS (TIC)	$ NA[b]
OTHER COSTS	
• Interest during construction	$ NA[b]
• Startup	NA[b]
• Other	NA[b]
TOTAL OTHER COSTS (TOC)	$ NA[b]
TOTAL CAPITAL COSTS (TCC = TDC + TIC + TOC)	$1,880,000
RELATIVE CAPITAL COSTS	
• TCC/design SLA flow rate	$ 173,000/Nm^3/sec ($82/scfm)
• TCC/design carbon charge	$ 106/kg ($48/lb)

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[a] All cost figures, unless otherwise noted, were obtained by scaling plant-supplied data to a late 1983 capital cost basis. Scaling factors were obtained from the Chemical Engineering Plant Cost Index; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Data not available. Plant 3 was able to supply only the total capital cost (TCC) figure.

TABLE 8-6. ANNUALIZED COSTS FOR THE SOLVENT RECOVERY SYSTEM AT MAGNETIC TAPE PLANT 3[a]

DIRECT COSTS	
• Labor	
--operating	$ 76,000
--maintenance	17,700
--laboratory	0
--supervisory	39,000
• Maintenance materials	16,000[c]
• Activated carbon	56,000
• Utilities	
--electricity	69,000
--steam	605,000
--cooling water	151,000[b]
--chilled water	0
TOTAL DIRECT COSTS (TDC)	$ 1,031,000/yr
INDIRECT COSTS	
• Capital recovery[c]	$ 306,000[c]
• Labor and plant overhead	46,000
• General and administrative	28,000
• Insurance and property tax	19,000[c]
TOTAL INDIRECT COSTS (TIC)	$ 399,000/yr
TOTAL ANNUALIZED COSTS (TAC = TDC + TIC)	$ 1,430,000/yr
RELATIVE ANNUALIZED COSTS	
• TAC/actual annual SLA throughput	$ 7.0/10^3Nm^3 ($0.20/$10^3$ scf)
• TAC/actual annual solvent recovery	$ 0.66/kg ($0.30/lb)

[a] All cost figures, unless otherwise noted, were obtained by multiplying plant-supplied unit costs (e.g., $/man-hour) by measured or plant-supplied operating rates (e.g., man-hours/week). Costs are expressed on a late 1983 basis; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

[c] Capital recovery = TCC x $\frac{(1+i)^n i}{(1+i)^n - 1}$

where TCC = total capital cost

i = interest rate @ 0.10

n = equipment life @ 10 years

SECTION 9

TEST RESULTS - PLANT 4

The carbon adsorption system at Plant 4, a flexible packaging plant, was tested in June 1982 and November 1983. Design specifications and a process description for the Plant 4 system are presented in this section, followed by results of the performance testing. Capital and annualized cost data are also presented.

PROCESS DESCRIPTION AND DESIGN SPECIFICATIONS

Plant 4 manufactures wax-coated aluminum foil for use in food packaging. In this manufacturing process, aluminum foil is unrolled from a coil and passed through a bath of petroleum wax dissolved in hexane. The hexane is volatilized from the foil in a drying oven and ducted with drying air to the solvent recovery system.

The solvent recovery system consists of three horizontal carbon beds and a solvent separation process. Design specifications for the carbon adsorption system are presented in Table 9-1. As shown, the system is a Raysolv, Incorporated design started up in 1979. The system is sized to process a 10.4 Nm^3/sec (22,000 scfm) SLA stream with an inlet hexane concentration of 4,340 ppmv. The guaranteed VOC control level is 96 percent.

A process flow diagram of the Plant 4 system is shown in Figure 9-1. As shown, the initial step in the solvent recovery process involves preconditioning of the SLA from the drying oven. The preconditioning process involves

TABLE 9-1. DESIGN SPECIFICATIONS FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 4

Design Parameter	Design Specification
MANUFACTURER	Raysolv, Inc.
STARTUP DATE	1979
CARBON BED SPECIFICATIONS	
Configuration	horizontal
Number of beds	3
Dimensions	
• length	5.2 m (17 ft)
• width	2.4 m (8 ft)
• depth	0.5 m (1.7 ft)
Carbon loading per bed	3,040 kg (6,700 lb)
Carbon type	Columbia JXC
Carbon base	petroleum
SLA SPECIFICATIONS	
Flow direction through beds	upward
Flow rate to carbon beds	10.4 Nm^3/sec (22,000 scfm)
Relative flow rate[a]	0.0017 Nm^3/sec - kg carbon (1.6 scfm/lb carbon)
Superficial bed velocity	0.44 m/sec (87 ft/min)
Residence time in bed	1.2 sec
Inlet temperature	35°C (95°F)
SOLVENT SPECIFICATIONS	
Type	hexane
Inlet mass loading	590 kg/hr (1,300 lb/hr)
Inlet concentration loading	4,340 ppmv
Relative inlet mass loading[a]	0.097 kg/kg carbon/hr (0.097 lb/lb carbon/hr)
REGENERATION SPECIFICATIONS	
Steam consumption	1,880 kg/hr (4,130 lb/hr)[b]
Steam/recovered solvent	NA[c]
Cooling/drying medium	exhaust air
SOLVENT REMOVAL EFFICIENCY	96%[d]
MATERIALS OF CONSTRUCTION	
Adsorber	stainless steel
Ductwork	aluminum/carbon steel
Piping	carbon steel
METHOD OF SOLVENT SEPARATION	decantation

[a] Refers to the solvent and SLA loadings to the carbon in the on-line (adsorbing) carbon beds.

[b] Per desorption.

[c] Data not available due to unspecified frequency of desorption.

[d] Guaranteed.

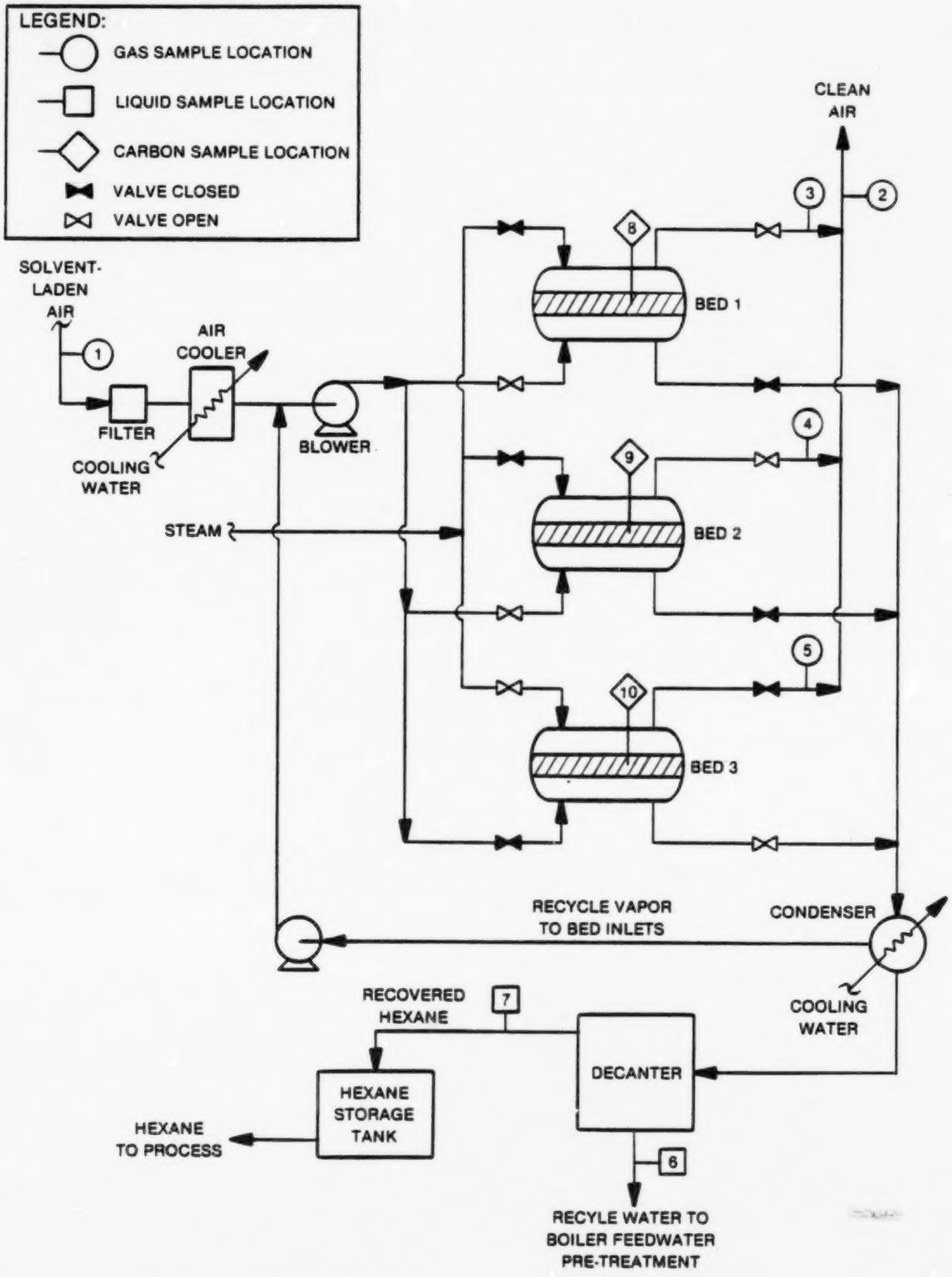
LEGEND:
GAS SAMPLE LOCATION
LIQUID SAMPLE LOCATION
CARBON SAMPLE LOCATION
VALVE CLOSED
VALVE OPEN
SOLVENT-LADEN AIR
1
FILTER
AIR COOLER
COOLING WATER
BLOWER
STEAM
CLEAN AIR
2
3
4
5
8
9
10
BED 1
BED 2
BED 3
RECYCLE VAPOR TO BED INLETS
CONDENSER
COOLING WATER
RECOVERED HEXANE
7
DECANTER
HEXANE STORAGE TANK
HEXANE TO PROCESS
6
RECYLE WATER TO BOILER FEEDWATER PRE-TREATMENT

Figure 9-1. Plant 4 solvent recovery system.

filtering and cooling of the SLA. After preconditioning, the SLA is introduced to the lower plenum of the two on-line carbon adsorbers (the third adsorber is in the regeneration mode). The SLA flows upward through the bed and is stripped of hexane content. The treated air is then exhausted through a common outlet stack to the atmosphere.

Regeneration of a spent carbon bed involves three distinct operating modes: desorption, expansion and "emission cut-back". During the desorption mode, low-pressure steam is passed downward through the carbon bed, stripping the carbon of solvent. The majority of the steam/hexane mixture is condensed; uncondensed vapors are recycled to the inlet of the adsorption section. The condensed water/hexane mixture is separated in a decanter, and the recovered hexane is sent to storage for reuse in the coating process. The water phase is treated and recycled to the plant boiler.

After the desorption portion of the regeneration cycle, the bed undergoes expansion, with the recycle blower (shown in Figure 9-1) evacuating the bed. Following expansion, the emission cut-back mode begins with the automatic opening of the treated air exhaust valve. The recycle blower then draws treated air from the two on-line beds in reverse flow through the regenerating bed, through the condenser, and back to the inlet of the adsorption system. This backflush of gases desorbs solvent remaining on the bed and also serves to partially cool the bed. Following bed regeneration, the bed is placed in the standby mode.

The sequencing of the adsorption/regeneration modes of the three beds is controlled by a timer. During the original test period in 1982, the lengths of the adsorption, desorption, expansion, emission cut-back (ECB) and standby modes were 120, 25, 5, 5 and 25 minutes per bed, respectively, for a total cycle time of 180 minutes. In the 17-month period of time before the repeat test period, however, the length of the adsorption period was reduced by plant personnel in response to decreasing rates of solvent recovery. Therefore, the cycle timing in effect during the repeat test period was set at 90, 25, 5, 5 and 10 minutes per bed for the adsorption, desorption, expansion, emission cut-back and standby modes, respectively, for a total cycle time of 135 minutes.

The sequencing of the various operating modes for the Plant 4 system during the original and repeat testing is shown below:

Segment	Bed 1	Bed 2	Bed 3	Time (Original)	Time (Repeat)
1	Ads	Des	Ads	25 min.	25 min.
2	Ads	Exp	Ads	5 min.	5 min.
3	Ads	ECB	Ads	5 min.	5 min.
4	Ads	Std	Ads	25 min.	10 min.
5	Ads	Ads	Des	25 min.	25 min.
6	Ads	Ads	Exp	5 min.	5 min.
7	Ads	Ads	ECB	5 min.	5 min.
8	Ads	Ads	Std	25 min.	10 min.
9	Des	Ads	Ads	25 min.	25 min.
10	Exp	Ads	Ads	5 min.	5 min.
11	ECB	Ads	Ads	5 min.	5 min.
12	Std	Ads	Ads	25 min.	10 min.

The solvent recovery system at Plant 4 is relatively well instrumented. The following instrumentation is available for process monitoring:

- a lighted control panel indicating each bed's operating status;

- timers indicating remaining time of each operating mode;

- a hydrocarbon analyzer for monitoring exhaust air solvent concentrations;

- a multipoint temperature recorder; and

- other temperature, pressure, and liquid level indicators at appropriate locations in the system.

With the exception of the exhaust air hydrocarbon analyzer, all process instrumentation was operational during the original and repeat testing.

TEST RESULTS

Testing of the Plant 4 carbon adsorption system focused on the characterization of: (1) general operating parameters; (2) VOC control performance; and (3) carbon, solvent and condensate properties. Results of these characterizations are presented in this section.

General Operating Parameters

Table 9-2 lists general operating conditions for the Plant 4 carbon adsorption system as measured during the original and repeat testing periods. The data are categorized as adsorption and regeneration mode data.

Comparison of the original and repeat adsorption mode data shows several significant differences in operation. In particular, differences in cycle timing were measured, as noted earlier. Adsorption mode lengths measured 120 minutes for the original testing and 90 minutes for the repeat testing.

Also, SLA throughput differed significantly for the two test periods. SLA flow rate averaged 8.3 Nm^3/sec (17.700 scfm) for the original test period but closely approximated the design capacity of 10.4 Nm^3/sec (22,000 scfm) during the repeat testing. The differences, which were confirmed by repeated measurements, were apparently related to different coating oven conditions.

TABLE 9-2. GENERAL OPERATING DATA FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 4

Operating Parameter	Operating Conditions[a]	
	Original Test - June, 1982	Repeat Test - November, 1983
Adsorption Mode		
Solvent type	Hexane	Hexane
Mode length	120 min	90 min
Inlet SLA flow rate	8.3 Nm^3/sec (17,700 scfm)	10.7 Nm^3/sec (22,600 scfm)
SLA superficial velocity	0.36 m/sec (70 ft/min)	0.46 m/sec (89 ft/min)
Bed residence time	1.5 sec	1.2 sec
SLA temperature drop across air cooler	29°C (52°F)	27°C (49°F)
Inlet SLA temperature (after air cooler)	32°C (89°F)	22°C (72°F)
Inlet SLA relative humidity	49%	40%
Carbon bed pressure drop	Bed 1 - 2.1 kPa (8.6 in. H_2O) Bed 2 - 2.1 kPa (8.5 in. H_2O) Bed 3 - 1.9 kPa (7.8 in. H_2O)	Bed 1 - 2.0 kPa (8.2 in. H_2O) Bed 2 - 2.1 kPa (8.3 in. H_2O) Bed 3 - 2.0 kPa (8.1 in. H_2O)
Outlet air flow rate	8.0 Nm^3/sec (16,900 scfm)[b]	9.7 Nm^3/sec (20,600 scfm)[b]
Outlet air temperature	42°C (108°F)	37°C (98°F)
Outlet air relative humidity	39%	26%
Regeneration Mode		
Desorption period length	25 min	25 min
Cooldown period length	10 min[c]	10 min[c]
Standby period length	25 min	10 min
Steam flow rate (per bed desorption)	1,450 kg/hr (3,200 lb/hr)[d]	1,500 kg/hr (3,300 lb/hr)[d]
Steam/recovered solvent ratio	4.6 kg/kg (4.6 lb/lb)[e]	10.9 kg/kg (10.9 lb/lb)[e]
Steam pressure	141 kPa (5.8 psig)	146 kPa (6.5 psig)
Steam temperature	109°C (229°F)	110°C (230°F)
Wastewater flow rate	302 kg/hr (666 lb/hr)[f,g]	416 kg/hr (916 lb/hr)[f,g]

[a] Average values are presented.

[b] Common outlet stack.

[c] Includes the expansion and emission cut-back periods (5 minutes each).

[d] Based on plant chart recordings.

[e] Based on measured VOC data and plant steam flow data.

[f] The "wastewater" is recycled as condensate to the boiler.

[g] Estimated from steam flow rate.

Finally, differences in adsorption mode gas temperatures and moisture levels were measured, primarily due to different ambient conditions, although temperatures and moisture levels were within the acceptable ranges.

Regeneration mode testing during the original and repeat test periods indicated similar steam flow rate and temperature. However, the steam/solvent ratios differed considerably, averaging 4.6 kg/kg (4.6 lb/lb) during the original testing and 10.9 kg/kg (10.9 lb/lb) during the repeat testing. The difference is primarily attributed to signifcantly different solvent recovery efficiencies with no change in steam use.

VOC Control Efficiency Performance

VOC control efficiency data for the original and repeat testing of the Plant 4 carbon adsorption system are summarized in Table 9-3. During the original testing, coating conditions were relatively constant, resulting in inlet VOC concentrations to the carbon adsorption system of 1,200 to 1,400 ppmv. VOC control efficiency averaged 99 percent for all three beds (the bed carbon had been in service for approximately three years). During the repeat testing approximately 18 months later, coating conditions were relatively unsteady, with average inlet VOC concentrations ranging from 50 to 1,000 ppmv. More significantly, VOC control efficiencies showed a marked decrease. Long-term monitoring of common inlet and outlet VOC concentrations during the repeat test period indicated a total solvent control level of less than 50 percent. Testing of individual beds showed VOC control levels of 94, 92 and 69 percent for Beds 1, 2 and 3, respectively.

Examination of typical VOC concentration profiles revealed the reason for the difference in control efficiency measured during the two test periods. Figure 9-2 shows a typical VOC concentration profile as measured in the common outlet stack over a complete cycle during the original test period. The 180-minute cycle consisted of three 60-minute segments, each of which was characterized by the regeneration of a different bed. The beginning of each

TABLE 9-3. VOC CONTROL EFFICIENCY DATA FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 4

	Inlet VOC Loading		Outlet VOC Emissions		VOC Control Efficiency,%[b],[c]
	Concentration ppmv[a],[b]	Mass Rate kg/hr (lb/hr)[a],[b]	Concentration ppmv[a],[b]	Mass Rate kg/hr (lb/hr)[a],[b]	
Original Test - June, 1982					
Common Inlet/ Outlet	1,260	138 (304)	13	1.4 (3.0)	99.0
Bed 1	1,210	66 (146)	7	0.40 (0.88)	99.4
Bed 2	1,230	83 (182)	11	0.73 (1.6)	99.1
Bed 3	1,380	93 (204)	16	1.0 (2.3)	98.9
Repeat Test - November, 1983					
Common Inlet/ Outlet	940	131 (289)	549	70 (154)	46.7
Bed 1	578	37 (81)	35	2.2 (4.9)	94.0
Bed 2	560	36 (79)	44	2.8 (6.2)	92.2
Bed 3	979	62 (137)	310	20 (43)	68.6

[a] As hexane.

[b] Average values are presented.

[c] Efficiency expressed on a system "basis."

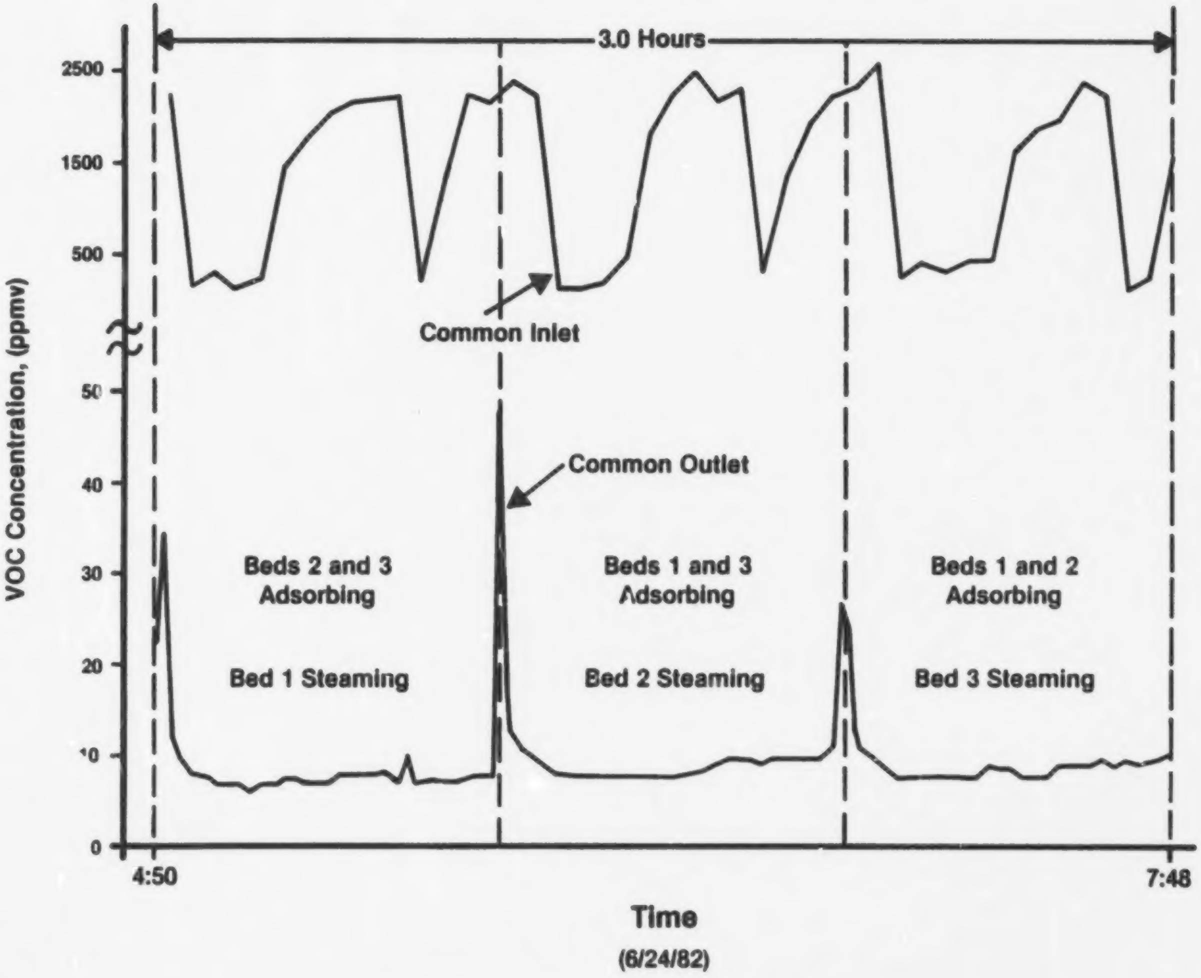

Figure 9-2. Plant 4 VOC concentration profiles - common inlet/outlet (original test period).

60-minute segment was marked by a sharp concentration spike (up to 50 ppmv) as a relatively warm and moisture-laden bed was placed into adsorption service. This response was typical of other tested systems.

By comparison, Figure 9-3 represents a typical outlet VOC concentration profile as measured in the common exhaust stack during the repeat test period. Again, the cycle (135 minutes) consisted of three segments, corresponding to regeneration of the three beds. As in the previous figure, each segment was marked by an initial concentration spike corresponding to a bed beging placed into absorption service. More significant, however, were the concentration peaks occurring approximately 15 minutes into each 45-minute segment. These concentration peaks represented major solvent losses, with the outlet VOC concentrations typically exceeding 2,000 ppmv. This phenomenon was not due to typical bed breakthrough, as the outlet VOC profile returned to the baseline level of less than 100 ppmv approximately 30 minutes into each segment. Rather, the concentration increases appeared to coincide with desorption of the off-line bed during each of the 45-minute segments. The cyclic nature of the concentration increase and corresponding decrease suggested that one or more of the steam inlet or outlet valves was leaking or improperly operating.

Examination of individual bed outlet VOC profiles, as in Figure 9-4, provided further explanation of the excessive VOC emissions during the repeat test period. A typical Bed 1 outlet VOC profile showed no excessive solvent losses, even at the end of the adosrption period. However, outlet concentration profiles for the other beds, especially Bed 3, showed distinct increases during both segments of the adsorption period, again corresponding to regeneration of the off-line bed. The profiles characteristic of Beds 2 and 3 suggested that the steam outlet valves on both beds were not closing properly when the beds were in adsorption service.

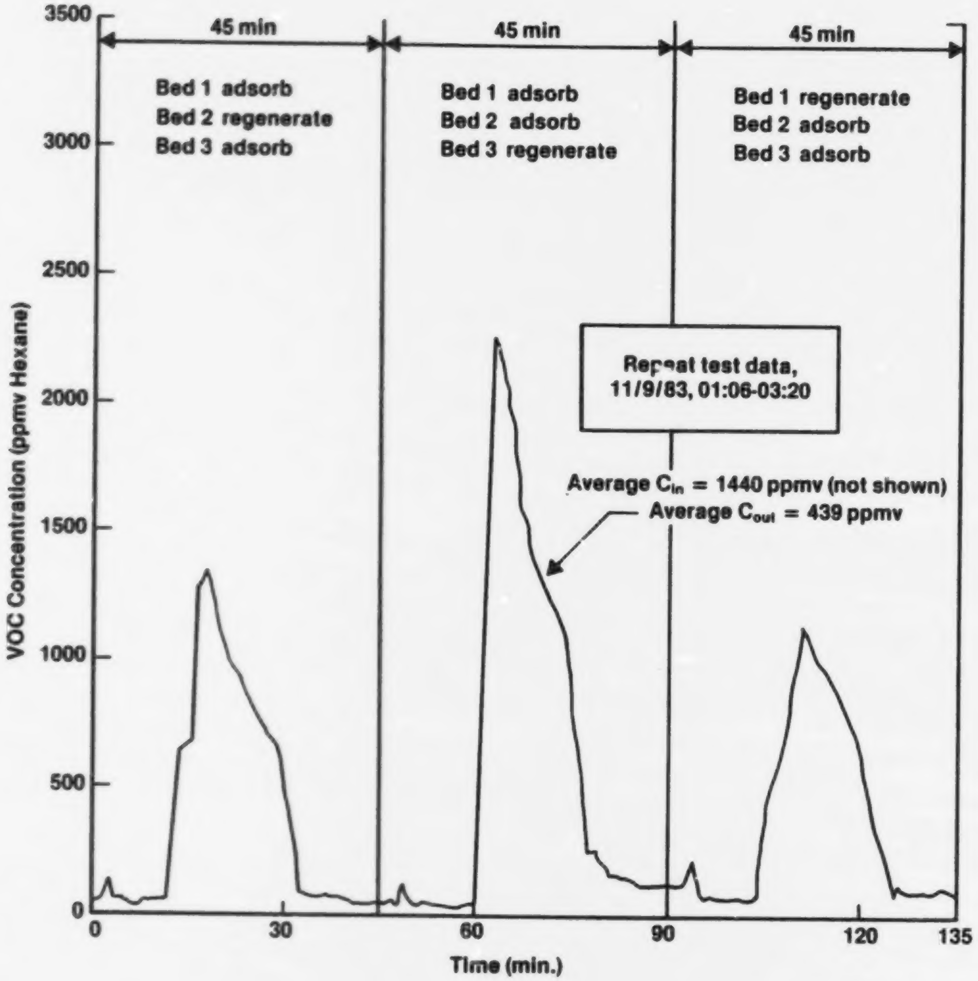

Figure 9-3. Plant 4 VOC concentration profiles - common outlet (repeat test period).

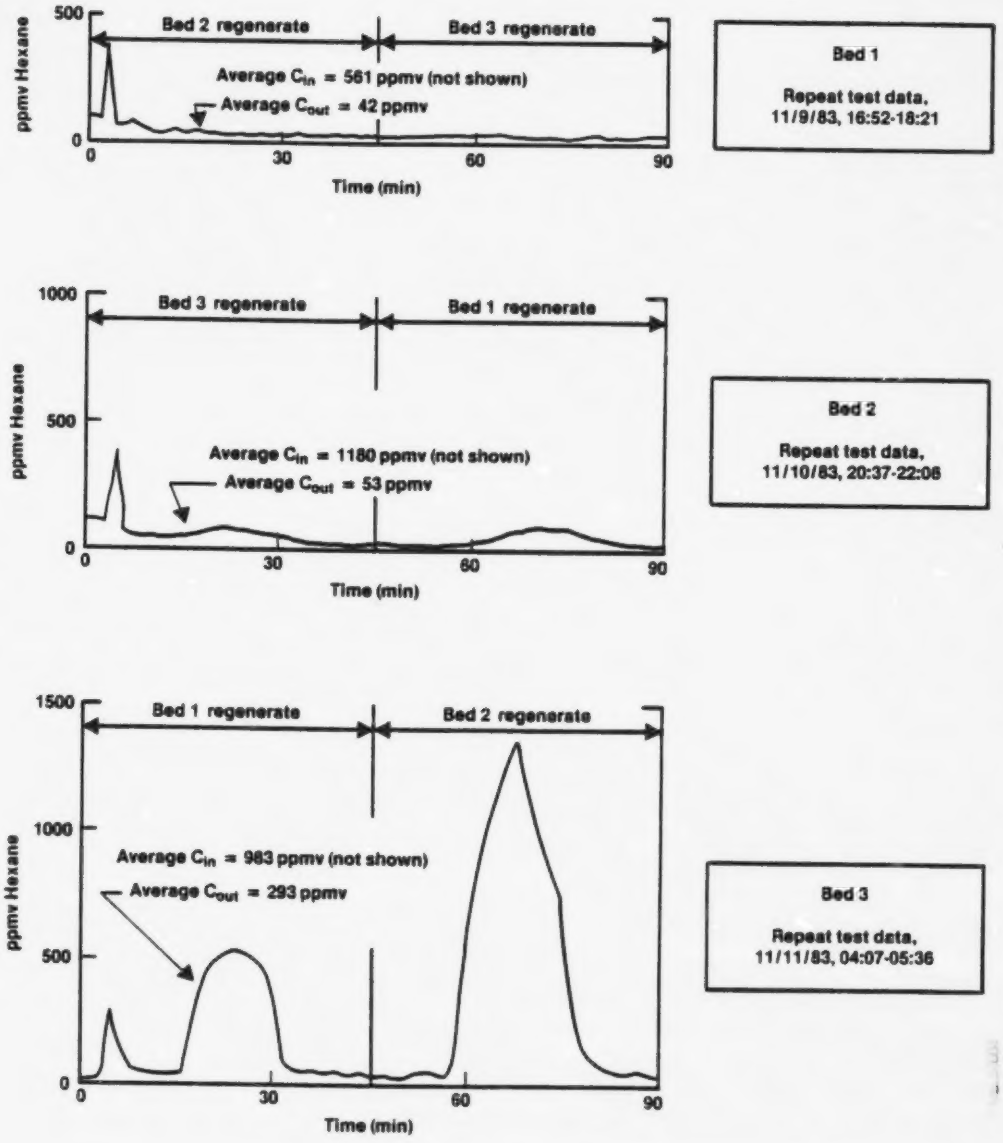

Figure 9-4. Plant 4 VOC concentration profiles - Beds 1, 2 and 3 individual outlet stacks (repeat test period).

Interestingly, none of the three beds exhibited typical breakthrough characteristics, with baseline solvent emission levels of about 20 ppmv. This result suggested that system performance for the repeat testing would not have been significantly different from the original performance if the solvent losses due to improper valve action had been discounted. (In fact, inspection of the steam outlet valves on Beds 2 and 3 by plant personnel several weeks after the repeat test period confirmed that the valves were severely corroded and leaking. The valves were replaced, and source testing by the plant subsequently showed a dramatic improvement in control efficiency, approximating that measured during the original test period.)

Periodic GC analysis of inlet and outlet air streams resulted in concentration data similar to the THC data. As expected, hexane was the only solvent VOC present in the inlet and outlet streams.

Carbon, Solvent and Condensate Characteristics

Characteristics of the carbon, solvent and condensate from the Plant 4 solvent recovery system are summarized in Table 9-4 and described below.

Analysis of the petroleum-bsed carbon from the Plant 4 system during the original test period (service life of 3.0 years) indicted a possible degradation in adsorption capacity relative to virgin carbon. Also, possible degradation in adsorption capacity also was measured for the bed carbon during the repeat test period approximately 1.5 years later. The volatiles content of the regenerated carbon was higher during the repeat test than the original test. This indicates that the regeneration of the bed during the repeat test may not have been as complete as during the original test.

Analysis of virgin and recovered solvent samples showed that the solvent supply used in the Plant 4 coating process consisted primarily of n-hexane and other hexane isomers.

TABLE 9-4. CHARACTERISTICS OF CARBON, SOLVENT, AND CONDENSATE FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 4

Parameter	Original Test Period June, 1982[a]						Repeat Test Period November, 1983[a]					
	Bed 1	Bed 2			Bed 3	Virgin	Bed 1		Bed 2		Bed 3	
Carbon Analysis[b]	Average[c]	Influent	Effluent	Average[c]	Average[c]		Influent	Effluent	Influent	Effluent	Influent	Effluent
Service life	3.0 yr	3.0 yr	3.0 yr	3.0 yr	3.0 yr	NA	4.5 yr	4.5 yr	4.5 yr	4.5 yr	4.5 yr	4.5 yr
CCl_4 activity, %	35	NM	NM	43	34	62	22	34	32	30	34	44
CCl_4 retentivity	17	NM	NM	19	16	42	6	15	NM	NM	NM	NM
Volatiles, %	NM	15	19	NM	NM	NM	20	26	22	20	NM	NM
Surface area, m^2/g	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Moisture, %	2	1	5	2	NM	NM	2	7	2	3	3	4
Particle size, mm[d]	4.2	NM	NM	4.1	4.2	4.2	3.8	NM	3.9	NM	3.9	NM
Solvent Analysis			Recovered Hexane		Virgin Hexane					Recovered Hexane		
n-Hexane, wt %			38.2		60.8					42.5		
Other, wt %[e]			61.8		39.2					57.3		
Water, wt %			<0.1		<0.1					0.2		
Condensate Analysis[f]												
n-Hexane, ppm (wt)			21							<1		
Other, ppm (wt)[e]			<1							66		

NA = Not applicable NM = Not measured

[a] Average values are presented.

[b] Carbon samples were collected after bed desorption.

[c] Represents a mixture of influent, middle, and effluent carbon samples.

[d] Sieve size through which 50% of the carbon sample weight passed.

[e] As hexane.

[f] Desorption steam condensate was recycled to the plant boiler.

These same compounds were detected in the decanter condensate, but at very low levels due to the relative insolubility of hexane and its isomers in water. For both test periods, the organic content of the condensate represented less than 0.1 percent of the total solvent processed by the solvent recovery system.

COST DATA

Cost data for the Plant 4 solvent recovery system are presented in this section. Included is a listing of the equipment represented by the cost data, followed by estimated capital and annualized costs.

Equipment List for Costing

The following major equipment items are included within the cost data supplied for the Plant 4 solvent recovery system:

- SLA transport equipment, including the SLA blower and ductwork from the oven;
- SLA preconditioning equipment, including the filter and air cooler;
- solvent adsorption equipment, consisting of the adsorber vessels and related equipment;
- solvent separation equipment, consisting of the solvent/water decanter; and
- solvent storage equipment, including the hexane storage tank and piping.

Capital Costs

Capital costs for the Plant 4 solvent recovery system are presented in Table 9-5. Costs are expressed in late 1983 dollars. As shown, the total estimated capital cost is \$1,334,000, or \$129,00/Nm^3/sec (\$61/scfm) on a unit SLA flow basis.

Annualized Costs

Estimated annualized costs for the Plant 4 system, in 1983 dollars, are presented in Table 9-6. As shown, total annualized costs approximate \$494,000 per year, with steam, capital recovery and cooling water representing the major cost components. On a recovered solvent unit basis, the total annualized cost corresponds to \$0.51/kg (\$0.23/lb) of solvent.

TABLE 9-5. CAPITAL COSTS FOR THE SOLVENT RECOVERY SYSTEM AT FLEXIBLE PACKAGING PLANT 4[a]

DIRECT COSTS	
• Delivered equipment	$ 761,000
• Installation materials (ducting, piping, foundations, buildings, electrical, instrumentation, insulation, painting, tankage, etc.)	380,000
• Installation labor	Included above
TOTAL DIRECT COSTS (TDC)	$ 1,141,000
INDIRECT COSTS	
• Engineering and supervision	$ 129,000
• Miscellaneous construction expenses	Included above
• Contractor's fees	Included above
• Contingencies	0
TOTAL INDIRECT COSTS (TIC)	$ 129,000
OTHER COSTS	
• Interest during construction	$ 0
• Startup	64,000[b]
• Other	0
TOTAL OTHER COSTS (TOC)	$ 64,000
TOTAL CAPITAL COSTS (TCC = TDC + TIC + TOC)	$ 1,334,000
RELATIVE CAPITAL COSTS	
• TCC/design SLA flow rate	\$ 129,000/Nm^3/sec (\$61/scfm)
• TCC/design carbon charge	\$ 145/kg (\$66/lb)

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[a] All cost figures, unless otherwise noted, were obtained by scaling plant-supplied data to a late 1983 capital cost basis. Scaling factors were obtained from the Chemical Engineering Plant Cost Index; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

TABLE 9-6. ANNUALIZED COSTS FOR THE SOLVENT RECOVERY SYSTEM AT FLEXIBLE PACKAGING PLANT 4[a]

DIRECT COSTS	
• Labor	
--operating	\$ 12,000[b]
--maintenance	8,000[b]
--laboratory	0[b]
--supervisory	1,000[b]
• Maintenance materials	11,000
• Activated carbon	8,000
• Utilities	
--electricity	29,000
--steam	99,000
--cooling water	45,000
--chilled water	0
TOTAL DIRECT COSTS (TDC)	\$ 214,000/yr
INDIRECT COSTS	
• Capital recovery[c]	\$ 217,000[b]
• Labor and plant overhead	19,000[b]
• General and administrative	13,000[b]
• Insurance and property tax	32,000[b]
TOTAL INDIRECT COSTS (TIC)	\$ 281,000/yr
TOTAL ANNUALIZED COSTS (TAC = TDC + TIC)	\$ 494,000/yr
RELATIVE ANNUALIZED COSTS	
• TAC/actual annual SLA throughput	\$ 2.5/10^3Nm^3 (\$0.07/10^3 scf)[d]
• TAC/actual annual solvent recovery	\$ 0.51/kg (\$0.23/lb)[d]

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[a] All cost figures, unless otherwise noted, were obtained by multiplying plant-supplied unit costs (e.g., \$/man-hour) by measured or plant-supplied operating rates (e.g., man-hours/week). Costs are expressed on a late 1983 basis; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

[c] Capital recovery = TCC x $\frac{(1+i)^n}{(1+i)^n - 1}$

[d] Based upon original test data.

where TCC = total capital cost
i = interest rate @ 0.10
n = equipment life @ 10 years

SECTION 10

TEST RESULTS - PLANT 5

The carbon adsorption system at Plant 5, a rubberized fabric manufacturer, was performance tested in July 1982 and November 1983. The Plant 5 system design specifications and process description are presented in this section, followed by results of the performance testing and capital and annualized cost data.

DESIGN SPECIFICATIONS AND PROCESS DESCRIPTION

Plant 5 manufactures rubberized fabric printing blankets for use in web offset printing. The fabric is coated in three coating lines, or spreaders. The manufacturing process involves dissolving rubber compounds in toluene, spreading the rubber/solvent slurry onto a fabric web, and volatilizing the toluene from the coated web in steam-heated drying ovens. The toluene vapor is then ducted with drying air to the solvent recovery system.

The solvent recovery system consists of three horizontal carbon beds and a solvent separation unit. Design specifications for the carbon adsorption system are presented in Table 10-1. As shown, the system is a Hoyt Manufacturing Company design started up in 1977 with an SLA capacity of 5.25 Nm^3/sec (11,100 scfm). The system is designed to process an inlet toluene concentration of 1,260 ppmv with a control efficiency of 97 percent.

A flow diagram of the Plant 5 system is shown in Figure 10-1. The first step in the solvent recovery process, SLA preconditioning, involves filtering and cooling of the SLA. After preconditioning, the SLA is delivered to the

TABLE 10-1. DESIGN SPECIFICATIONS FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 5

Design Parameter	Design Specification
MANUFACTURER	Hoyt Manufacturing Co.
STARTUP DATE	1977
CARBON BED SPECIFICATIONS	
Configuration	horizontal
Number of beds	3
Dimensions	
• length	3.0 m (10 ft)
• width	1.8 m (6 ft)
• depth	0.6 m (2 ft)
Carbon loading per bed	1,730 kg (3,800 lb)
Carbon type	Union Carbide JXC
Carbon base	acid sludge coke
SLA SPECIFICATIONS	
Flow direction through beds	downward
Flow rate to carbon beds	5.25 Nm^3/sec (11,100 scfm)
Relative flow rate[a]	0.0015 Nm^3/sec - kg carbon (1.5 scfm/lb carbon)
Superficial bed velocity	0.47 m/sec (92 ft/min)
Residence time in bed	1.3 sec
Inlet temperature	38°C (100°F)
SOLVENT SPECIFICATIONS	
Type	toluene
Inlet mass loading	92.6 kg/hr (204 lb/hr)
Inlet concentration loading	1,260 ppmv
Relative inlet mass loading[a]	0.027 kg/kg carbon/hr (0.027 lb/lb carbon/hr)
REGENERATION SPECIFICATIONS	
Steam consumption	531 kg/hr (1,170 lb/hr)[b]
Steam/recovered solvent	NA[c]
Cooling/drying medium	SLA
SOLVENT REMOVAL EFFICIENCY	97%
MATERIALS OF CONSTRUCTION	
Adsorbers	carbon and stainless steel
Ductwork	carbon and stainless steel
Piping	stainless steel
METHOD OF SOLVENT SEPARATION	decantation

[a] Refers to the solvent and SLA loadings to the carbon in the on-line (adsorbing) carbon beds.

[b] Per desorption.

[c] Data not available due to unspecified frequency of desorption.

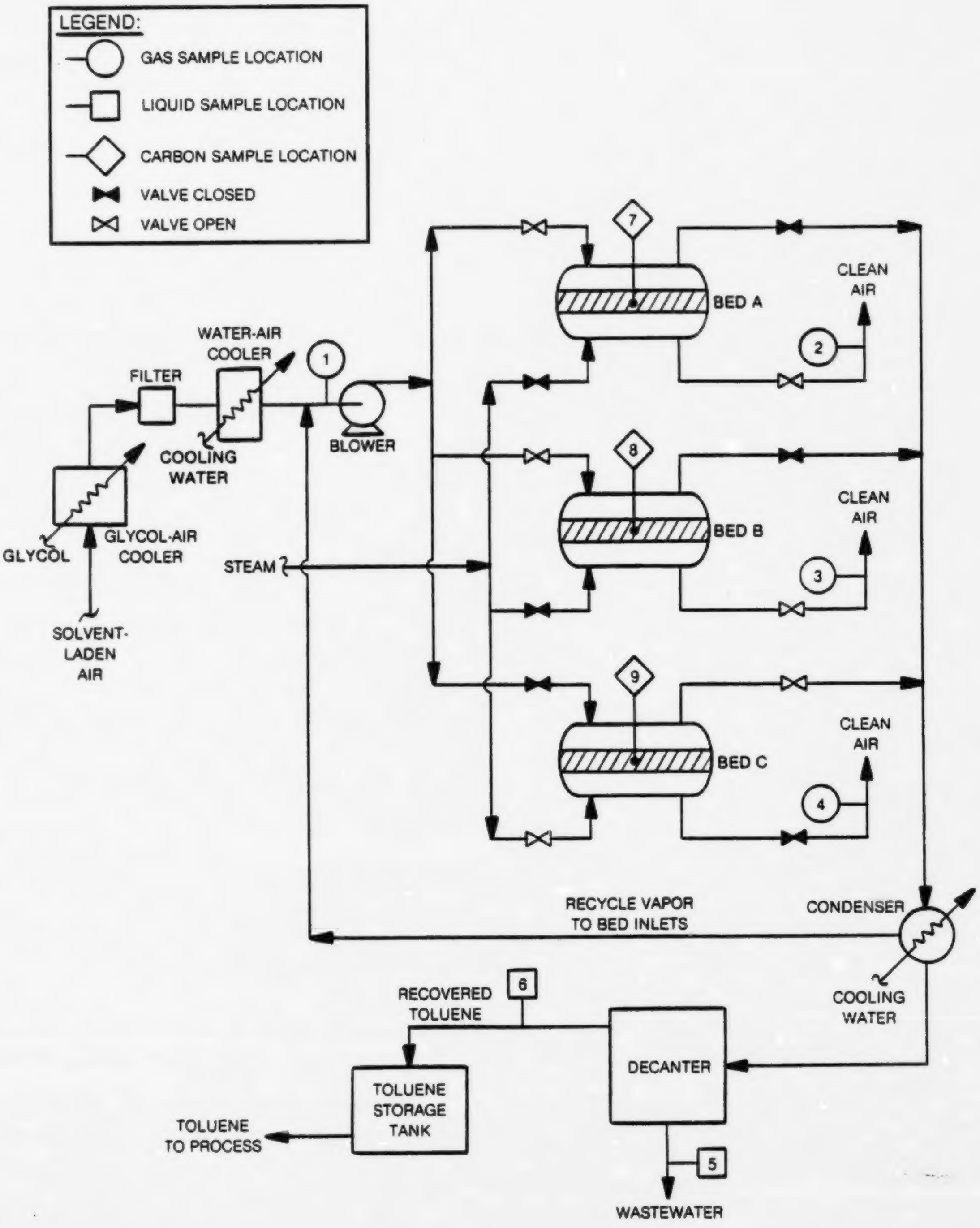
LEGEND:
GAS SAMPLE LOCATION
LIQUID SAMPLE LOCATION
CARBON SAMPLE LOCATION
VALVE CLOSED
VALVE OPEN
FILTER
WATER-AIR COOLER
COOLING WATER
1
BLOWER
GLYCOL
GLYCOL-AIR COOLER
SOLVENT-LADEN AIR
STEAM
7
BED A
CLEAN AIR
2
8
BED B
CLEAN AIR
3
9
BED C
CLEAN AIR
4
RECYCLE VAPOR TO BED INLETS
CONDENSER
COOLING WATER
RECOVERED TOLUENE
6
DECANTER
TOLUENE STORAGE TANK
TOLUENE TO PROCESS
5
WASTEWATER

Figure 10-1. Plant 5 solvent recovery system.

upper plenums of two on-line carbon adsorbers (the third absorber is being regenerated). The SLA flows downward through the beds, is stripped of toluene, and is exhausted to the atmosphere through individual exhaust stacks.

When a bed completes its adsorption cycle, it is closed off to SLA flow and desorbed with countercurrently flowing low-pressure steam. Most of the resulting steam/toluene mixture is condensed; uncondensed vapors and inerts are recycled to the inlet of the carbon adsorption system. The condensate is separated into solvent and water phases by decantation. The recovered toluene is sent to storage for reuse in the coating process, and the water is discharged to the sewer.

Following desorption, the bed is cooled and dried with SLA. The cooling air is exhausted to the atmosphere during this period, and all three beds are open to SLA flow. After cooling and drying is complete, the regenerated bed is placed into standby.

The sequencing of the adsorption/regeneration modes of the three beds is controlled by a timer. During the original test program in 1982, the system cycle timing was set at 150, 50, 15 and 10 minutes for the adsorption, desorption, cooling and standby modes, respectively, per bed. Therefore, the total cycle time was 225 minutes.

During the repeat test period in November 1983, significant variations in the cycle timing were encountered. A minor component of the variation was caused by adjustments of the timing by operating personnel, approximately once per shift. The timing was adjusted based on solvent loading levels that were expected for the upcoming shift. Adjustments were made only in the length of the adsorption mode, ranging from 180 to 210 minutes in length. (The lengths of the desorption and cooling modes were fixed at 40 and 10 minutes, respectively.) Therefore, total cycle times ranged from 270 to 315 minutes (including the 40- to 55-minute standby period).

More pronounced variations in cycle timing were caused by malfunctions in the timer. During the week of repeat testing, the system "jumped time" on several occasions; i.e., a newly regenerated bed would re-enter the regeneration mode while a bed normally due for regeneration would remain in adsorption service. Obviously, this condition contributed to off-design performance and limited the number of "representative" cycles that were avalable for analysis.

The cycle timing during the two test periods is compared below:

Segment	Bed A	Bed B	Bed C	Time (Original)	Time (Repeat)
1	Ads	Des	Ads	50 min.	40 min.
2	Ads	Cool	Ads	15 min.	10 min.
3	Ads	Std	Ads	10 min.	40-55 min.
4	Ads	Ads	Des	50 min.	40 min.
5	Ads	Ads	Cool	15 min.	10 min.
6	Ads	Ads	Std	10 min.	40-55 min.
7	Des	Ads	Ads	50 min.	40 min.
8	Cool	Ads	Ads	15 min.	10 min.
9	Std	Ads	Ads	10 min.	40-55 min.

The operation of the Plant 5 solvent recovery system is monitored with the following instrumentation:

- a lighted control panel indicating the operating status of each bed,
- a timer indicating the remaining time in each operating mode, and
- temperature indicators for each carbon bed.

With the exception of occasional malfunctions of the cycle timer mechanism, all instrumentation was operational during both the original and repeat test periods.

TEST RESULTS

Testing of the Plant 5 carbon adsorption system included the characterization of: (1) general operating parameters; (2) VOC control efficiency; and (3) carbon, solvent and wastewater properties. Results of these characterizations are presented in this section.

General Operating Parameters

General operating conditions for the Plant 5 carbon adsorption system during the original and repeat test periods are compared in Table 10-2. The data are categorized as adsorption and regeneration mode data.

The adsorption mode data for the original and repeat tests of Plant 5 show significant variations from the design values and between test periods. The most significant deviations are those related to SLA throughput, system temperatures, and the length of the adsorption mode.

The SLA flow rate to the Plant 5 carbon adsorption system averaged only 82 and 70 percent of the design value for the original and repeat test periods, respectively. This variation caused corresponding decreases in superficial velocity. The variations were attributed to different coating oven ventilation conditions.

Perhaps more significant were the variations in operating temperatures. The system operated at near-design temperatures during the original testing, but the repeat testing indicated adsorption temperatures that significantly exceeded optimum temperatures for typical adsorption systems. Specfically, inlet SLA temperatures during the repeat testing averaged 56°C (132°F), compred to the design value of 38°C (100°F). The increase in temperature was caused by the failure of the air cooler to provide adequate cooling of the SLA, perhaps as a result of blocked cooling water tubes. The air cooler lowered the SLA temperature by only 3°C (5°F) during the repeat test period, compared to 24°C (43°F) during the original test period.

TABLE 10-2. GENERAL OPERATING DATA FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 5

Operating Parameter	Operating Conditions[a]	
	Original Test - July, 1982	Repeat Test - November, 1983
Adsorption Mode		
Solvent type	Toluene	Toluene
Mode length	150 min	200 min
Inlet SLA flow rate	4.3 Nm^3/sec (9,100 scfm)	3.7 Nm^3/sec (7,800 scfm)
SLA superficial velocity	0.38 m/sec (75 ft/min)	0.33 m/sec (65 ft/min)
Bed residence time	1.6 sec	1.8 sec
SLA temperature drop across air cooler	24°C (43°F)	3°C (5°F)
Inlet SLA temperature (after air cooler)	40°C (104°F)	56°C (132°F)
Inlet SLA relative humidity	37%	10%
Carbon bed pressure drop	Bed A - 3.9 kPa (16.2 in. H_2O)	Bed A - 3.6 kPa (15.0 in. H_2O)
	Bed B - 4.0 kPa (16.6 in. H_2O)	Bed B - 3.5 kPa (14.7 in. H_2O)
	Bed C - 4.0 kPa (16.6 in. H_2O)	Bed C - 3.7 kPa (15.3 in. H_2O)
Outlet air flow rate	Bed A - 2.2 Nm^3/sec (4,600 scfm)	Bed A - 1.8 Nm^3/sec (3,900 scfm)
	Bed B - 2.0 Nm^3/sec (4,300 scfm)	Bed B - 1.7 Nm^3/sec (3,600 scfm)
	Bed C - 2.0 Nm^3/sec (4,300 scfm)	Bed C - 1.9 Nm^3/sec (4,000 scfm)
Outlet air temperature	37°C (99°F)	54°C (130°F)
Outlet air relative humidity	46%	14%
Regeneration Mode		
Desorption period length	50 min	40 min
Cooldown period length	15 min	10 min
Standby period length	10 min	50 min
Steam flow rate (per bed desorption)	1,360 kg/hr (3,000 lb/hr)[b]	1,270 kg/hr (2,800 lb/hr)[b]
Steam/recovered solvent ratio	8.2 kg/kg (8.2 lb/lb)[c]	14.8 kg/kg (14.8 lb/lb)[c]
Steam pressure	169 kPa (9.8 psig)	157 kPa (8 psig)
Steam temperature	115°C (239°F)	113°C (235°F)
Wastewater flow rate	454 kg/hr (1,000 lb/hr)[d]	261 kg/hr (574 lb/hr)[d]

[a] Average values are presented.

[b] Estimated from wastewater flow rate measurement.

[c] Based on measured VOC data and estimated steam flow data.

[d] Integrated value, based on measured data.

Finally, as discussed above, the cycle timing at Plant 5 differed during the original and repeat test periods. During the repeat test period, the cycle timing was adjusted so as to increase the average adsorption time per bed. This adjustment was made by operating personnel in response to lower inlet solvent loadings caused by lower coating production rates.

Significant results of the regeneration mode testing at Plant 5 are represented by the steam consumption rate and the steam/solvent ratio. The estimated steam consumption rate was similar for both test periods, nominally 1,300 kg/hr (2,860 lb/hr), but was significantly higher than the design value of 531 kg/hr (1,170 lb/hr). The steam/solvent ratios during both test periods were high, averaging 8.2 and 14.8 kg/kg (8.2 and 14.8 lb/lb) for the original and repeat test periods, respectively. Key factors contributing to the high steam/solvent ratios were higher-than-design desorption steam rates and lower-than-design solvent control efficiencies.

VOC Control Efficiency Performance

VOC control efficiency data for the original and repeat testing of the Plant 5 carbon adsorption system are summarized in Table 10-3. During the original testing, with five-year old carbon and inlet solvent concentrations approaching 2,000 ppmv, the three beds achieved control efficiencies of 97 percent or higher. Repeat testing with the same carbon 16 months later at significantly reduced inlet loading levels showed control efficiencies of 91, 52 and 98 percent for Beds A, B and C, respectively. (All control efficiency values are expressed on a "bed" basis; i.e., VOC contributions by the gas recycle stream were included in control efficiency calculations.) As suggested by the tabulated data, Beds A and C had generally comparable VOC removal performance for the two test periods. However, Bed B suffered a severe degradation in performance between the test periods.

TABLE 10-3. VOC CONTROL EFFICIENCY DATA FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 5

Test	Inlet VOC Loading		Outlet VOC Emissions		VOC Control Efficiency, %[b],[c]
	Concentration, ppmv[a],[b]	Mass Rate, kg/hr (lb/hr)[a],[b]	Concentration, ppmv[a],[b]	Mass Rate, kg/hr (lb/hr)[a],[b]	
Original Test - July, 1982					
Bed A	1,940	58.6 (129)	58	1.8 (3.9)	97.0
Bed B	1,920	55.4 (122)	46	1.3 (2.9)	97.6
Bed C	1,960	55.8 (123)	33	1.0 (2.1)	98.3
Repeat Test - November, 1983					
Bed A	734	19.0 (41.8)	63	1.6 (3.6)	91.4
Bed B	983	23.7 (52.1)	467	11.3 (24.8)	52.3
Bed C	972	26.0 (57.2)	21	0.6 (1.2)	97.8

[a] As toluene.

[b] Average values are presented.

[c] Efficiency expressed on a "bed" basis.

The following factors apparently contributed to the reduced performance of Bed B:

- leaking steam inlet and outlet valves on Bed B (as confirmed after the repeat test period),
- variations in cycle timing due to operator adjustment and timer malfunctions,
- significantly higher operating temperatures,
- reduced inlet concentrations (a lower driving force for the adsorption mechanism), and
- increased carbon age (lower activity).

These factors are discussed below.

The difference in Bed B performance during the original and repeat testing periods is illustrated by the VOC concentration profiles in Figure 10-2. The top portion of the figure shows performance data measured for Bed B during the original 1982 testing. During this example cycle, inlet toluene concentrations averaged 1,880 ppmv, as all three spreaders were in operation most of the time. The concentration of toluene exhausted from the bed slowly increased from 20 to 100 ppmv through the 150-minute adsorption time period; conversely, the concentration decreased from 100 to 20 ppmv through the 15-minute cooling/drying period. The time-weighted average exhaust VOC concentration over these two periods was 45 ppmv.

The lower portion of Figure 10-2 shows the degradation in performance measured during the repeat testing of Bed B approximately 16 months later. The measured inlet solvent concentration was erratic and averaged less than 1,000 ppmv, reflecting the lower production rates of the three spreaders.

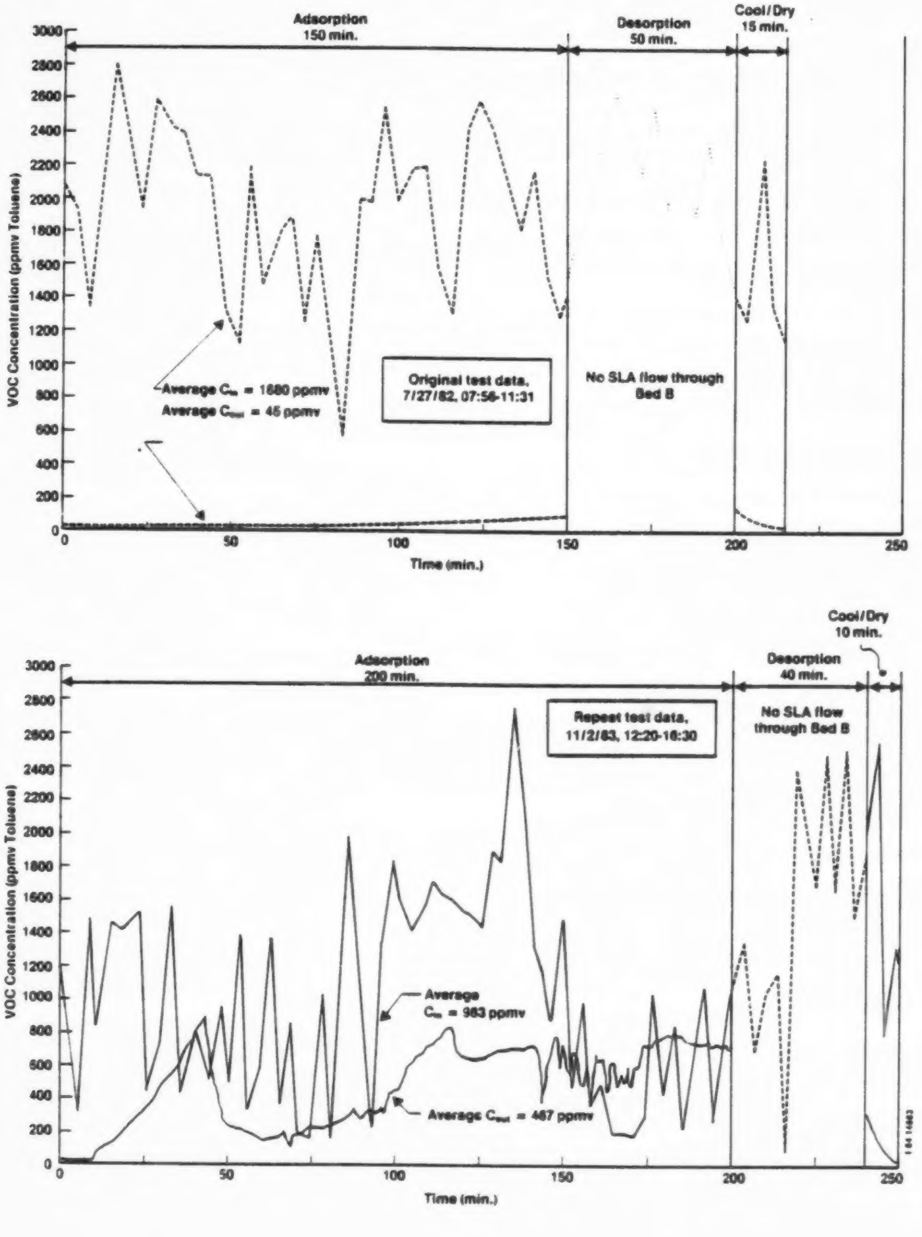

Figure 10-2. Plant 5 VOC concentration profiles - Bed B.

During this same period, the outlet VOC concentration averaged about 500 ppmv, with a significant portion of the total solvent emissions present as concentration spikes at 40 and 120 minutes. These spikes coincide with desorption of the other two beds and indicate that a steam inlet or exhaust valve on Bed B was leaking, allowing the carbon temperature to increase with an accompanying decrease in adsorption capacity. This temperature rise was confirmed during monitoring of the Bed B temperatures, which showed increases from 54°C (130°F) to 74°C (165°F) during desorption of the other two beds.

VOC concentration profiles for Beds A and C during both test periods resembled characteristic breakthrough curves, i.e., without the concentration spikes as measured for Bed B during the repeat test period. The shape of the curves was similar for both test periods and resembled the VOC concentration profiles shown in the upper portion of Figure 10-2.

Periodic GC analysis of the inlet SLA stream indicated toluene concentrations approximately equivalent to the measured THC concentrations. Low levels of hexane were also measured (hexane was periodically added to the coating slurry as a thinning agent). GC analysis of the exhaust stream also resulted in measurements of toluene concentrations similar to those measured by the THC analysis. In addition, hexane was present in the exhaust stream at relatively low levels in comparison to the toluene but proportionally higher than in the inlet SLA.

Carbon, Solvent and Wastewater Characteristics

Table 10-4 presents a summary of carbon, solvent and wastewater characteristics of the Plant 5 solvent recovery system. The results are discussed below.

As shown, the acid sludge coke-based carbon in place during the original testing (service life of 5.0 years) had similar adsorption capacities for all three beds, as evidenced by the CCl_4 activity and volatiles content data.

TABLE 10-4. CHARACTERISTICS OF CARBON, SOLVENT, AND WASTEWATER FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 5

Parameter	Original Test Period July, 1982^a						Repeat Test Period November, 1983^a				
	Bed A	Bed B			Bed C	Virgin	Bed A	Bed B			Bed C
	Average^c	Influent	Effluent	Average^c	Average^c		Average^c	Influent	Effluent	Average^c	Average^c
Carbon Analysis^b											
Service life	5.0 yr	5.0 yr	5.0 yr	5.0 yr	5.0 yr	NA	6.5 yr	6.5 yr	6.5 yr	6.5 yr	6.5 yr
CCl_4 activity, %	38	NM	NM	44	39	60	12	6	22	18	13
CCl_4 retentivity, %	19	NM	NM	21	20	NM	2	NM	NM	3	2
Volatiles, %	NM	22	15	NM	NM	NM	NM	25	24	NM	NM
Surface area, m^2/g	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
Moisture, %	3	1	1	4	3	2	<1	<1	<1	<1	2
Particle size, mm^d	2.3	NM	NM	4.2	3.9	4.2	NM	NM	3.9	NM	NM
Solvent Analysis			Recovered Toluene						Recovered Toluene		
Toluene, wt %			94.8						98.7		
Other, wt %^{e}			5.2						1.3		
Water, wt %			NM						<0.1		
Wastewater Analysis											
Toluene, ppm (wt)			380						8		
Other, ppm (wt)			93						140		

NA = Not applicable NM = Not measured

[a] Average values are presented.

[b] Carbon samples were collected after bed desorption.

[c] Represents a mixture of influent, middle, and effluent carbon samples.

[d] Sieve size through which 50% of the carbon sample weight passed.

[e] As hexane.

This result is consistent with the similar VOC control efficiencies measured for the three beds during the original testing. The bed carbon activity measured during the repeat testing 1.5 years later showed marked reduction, while the volatiles content showed a slight increase. The VOC removal efficiencies were generally lower during the repeat testing but no definitive level could be measured because the bed timer was malfunctioning.

Particle sizing data for the three beds show considerable variation. In particular, Bed A contained finer carbon than the other two beds. This phenomenon may have been related to attrition or to the original loading of the bed with carbon of a finer size fraction.

Analysis of recovered solvent samples showed toluene purity levels of 95 to 99 percent. Hexane, used as a cleanup solvent, represented the balance of the recovered solvent.

The wastewater from the decanter underflow contained nominally 200 to 500 ppm organic content. This organic content represented approximately 0.3 percent of the solvent processed by the solvent recovery unit.

COST DATA

Cost data for the Plant 5 solvent recovery system are presented in this section. The presented information includes a list of equipment, capital costs and annualized costs.

Equipment List for Costing

The following major equipment items are included within the cost data supplied for the PLant 5 solvent recovery system:

- SLA transport equipment, including ductwork from the spreader ovens and the SLA blower;

- SLA preconditioning equipment, including the filter and air coolers;
- solvent adsorption equipment, consisting of the adsorber vessels and related equipment;
- solvent separation equipment; and
- solvent storage tanks and associated piping.

Specifically excluded from the cost data are equipment items associated with solvent/coating blending, surface coating and web drying (ovens).

Capital Costs

Capital costs for the Plant 5 solvent recovery system are listed in Table 10-5. Costs are expressed in late 1983 dollars. As shown, the total estimated capital cost is $267,000, which corresponds to a unit capacity cost of $51,000/Nm^3/sec ($24/scfm).

Annualized Costs

Estimted annualized costs for the Plant 5 system, in 1983 dollars, are presented in Table 10-6. As shown, total annualized costs approximate $125,000 per year, with steam, capital recovery and electricity representing the major cost items. The total annualized cost corresponds to a unit cost of $0.19/kg ($0.09/lb) of recovered solvent.

TABLE 10-5. CAPITAL COSTS FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 5[a]

DIRECT COSTS	
• Delivered equipment	$ 147,000
• Installation materials (ducting, piping, foundations, buildings, electrical, instrumentation, insulation, painting, tankage, etc.)	78,000
• Installation labor	19,000[b]
TOTAL DIRECT COSTS (TDC)	$ 244,000
INDIRECT COSTS	
• Engineering and supervision	$ 10,000[b]
• Miscellaneous construction expenses	0[b]
• Contractor's fees	0[b]
• Contingencies	0
TOTAL INDIRECT COSTS (TIC)	$ 10,000
OTHER COSTS	
• Interest during construction	$ 0[b]
• Startup	13,000[b]
• Other	0[b]
TOTAL OTHER COSTS (TOC)	$ 13,000
TOTAL CAPITAL COSTS (TCC = TDC + TIC + TOC)	$ 267,000
RELATIVE CAPITAL COSTS	
• TCC/design SLA flow rate	\$ 51,000/Nm^3/sec (\$24/scfm)
• TCC/design carbon charge	$ 51/kg (23/lb)

[a] All cost figures, unless otherwise noted, were obtained by scaling plant-supplied data to a late 1983 capital cost basis. Scaling factors were obtained from the Chemical Engineering Plant Cost Index; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

TABLE 10-6. ANNUALIZED COSTS FOR THE CARBON ADSORPTION SYSTEM AT RUBBERIZED FABRIC PLANT 5[a]

DIRECT COSTS	
• Labor	
--operating	$ 0
--maintenance	2,000
--laboratory	0
--supervisory	6,000
• Maintenance materials	1,000
• Activated carbon	1,000[b]
• Utilities	
--electricity	18,000
--steam	32,000
--cooling water	11,000[b]
--chilled water	0
TOTAL DIRECT COSTS (TDC)	$ 72,000/yr
INDIRECT COSTS	
• Capital recovery[c]	$ 43,000[b]
• Labor and plant overhead	<1,000[b]
• General and administrative	3,000[b]
• Insurance and property tax	6,000[b]
TOTAL INDIRECT COSTS (TIC)	$ 53,000/yr
TOTAL ANNUALIZED COSTS (TAC = TDC + TIC)	$ 125,000/yr
RELATIVE ANNUALIZED COSTS	
• TAC/actual annual SLA throughput	$ 1.3/10^3Nm^3 (\$0.04/10^3 scf)[d]
• TAC/actual annual solvent recovery	$ 0.19/kg (\$0.09/lb)[d]

[a] All cost figures, unless otherwise noted, were obtained by multiplying plant-supplied unit costs (e.g., \$/man-hour) by measured or plant-supplied operating rates (e.g., man-hours/week). Costs are expressed on a late 1983 basis; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

[c] Capital recovery = TCC x $\frac{(1+i)^n i}{(1+i)^n - 1}$

where TCC = total capital cost
i = interest rate @ 0.10
n = equipment life @ 10 years

[d] Based upon original test data.

SECTION 11

TEST RESULTS - PLANT 6

The carbon adsorption system at Plant 6, a flexible packaging plant, was performance tested in August 1982 and November 1983. The Plant 6 system design specifications and process description are presented in this section, followed by results of the performance testing and capital and annualized cost data.

DESIGN SPECIFICATIONS AND PROCESS DESCRIPTION

Plant 6 manufactures flexible packagings for tobacco, food and health care products. Printing on the packaging material is applied in rotogravure presses and other proprietary coating operations with inks borne in a multi-component solvent formulation consisting mostly of toluene and isopropyl acetate (IPAC). After printing, the packaging material is dried in gas-fired or steam-heated ovens. The solvent is volatilized from the printed material and is swept with drying air to the solvent recovery system.

The solvent recovery system consists of an adsorption section, featuring six horizontal carbon beds and a distillation section. Design specifications for the system are presented in Table 11-1. As shown, the unit was designed and built by M&W Mechanical Contractors, Incorporated, and was started up in 1982. The system is designed to process an SLA flow of 37.8 Nm^3/sec (80,000 scfm) with an inlet toluene/IPAC concentration of 670 ppmv. The system is guaranteed to control solvent emissions at a performance level of 97 percent. A unique feature of the design specifications is the inclusion in the system

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TABLE 11-1. DESIGN SPECIFICATIONS FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 6

Design Parameter	Design Specification
MANUFACTURER	M&W Mechanical Contractors, Inc.
STARTUP DATE	1982
CARBON BED SPECIFICATIONS	
Configuration	horizontal
Number of beds	6
Dimensions	
• length	12.2 m (40 ft)
• width	2.7 m (9 ft)
• depth	0.9 m (3 ft)
Carbon loading per bed	13,900 kg (30,600 lb)
Carbon type	Calgon BPL
Carbon base	coal
SLA SPECIFICATIONS	
Flow direction through beds	upward
Flow rate to carbon beds	37.8 Nm^3/sec (80,000 scfm)
Relative flow rate[a]	0.00069 Nm^3/sec - kg carbon (0.65 scfm/lb carbon)
Superficial bed velocity	0.31 m/sec (61 ft/min)
Residence time in bed	3.0 sec
Inlet temperature	49°C (120°F)[b]
SOLVENT SPECIFICATIONS	
Type	60% toluene/40% IPAC
Inlet mass loading	370 kg/hr (810 lb/hr)
Inlet concentration loading	670 ppmv
Relative inlet mass loading[a]	0.0066 kg/kg carbon/hr (0.0066 lb/lb carbon/hr)
REGENERATION SPECIFICATIONS	
Steam consumption	535 kg/hr (1,180 lb/hr)[c]
Steam/recovered solvent	1.5 kg/kg (1.5 lb/lb)[d]
Cooling/drying medium	ambient air
SOLVENT REMOVAL EFFICIENCY	97%[d]
MATERIALS OF CONSTRUCTION	
Adsorbers	stainless steel
Ductwork	stainless steel
Piping	stainless steel
METHOD OF SOLVENT SEPARATION	distillation

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[a] Refers to the solvent and SLA loadings to the carbon in the on-line (adsorbing) carbon beds.

[b] Maximum.

[c] Average (integrated) value, based upon steam/recovered solvent ratio and inlet solvent mass loading.

[d] Guaranteed.

guarantee of a steam/recovered solvent ratio of less than or equal to 1.5 kg/kg (1.5 lb/lb). This value is considerably less than those reported for most typical systems.

A process flow diagram of the Plant 6 solvent recovery system is shown in Figure 11-1. As shown, the solvent recovery system consists of two parallel and identical process trains. Each process train handles half of the total inlet SLA flow and each train operates independently of the other. The SLA flow to each process train is filtered, cooled and introduced to the lower plenum of the two on-line horizontal carbon beds (the third bed is in the regeneration or standby mode). The SLA flows upward through the bed and is stripped of solvent content. The treated air is exhausted to the atmosphere through individual stacks.

When an absorbing bed becomes spent (breaks through), the adsorber vessel is closed off to SLA flow. Simultaneously, medium-pressure desorption steam is introduced to the plenum above the bed. The steam flows downward through the bed, countercurrent to the previous SLA flow. The steam strips solvent from the carbon, and the steam/solvent mixture exits the bed. The steam/solvent mixture enters a water-cooled condenser and a cyclone, where liquid and noncondensible vapors are separated. The vapors are recycled to the on-line adsorbers, and the condensate flows to the distillation section. In the distillation section, the condensate is separated into solvent and water fractions. The solvent is reused in the printing operation, and the wastewater is discharged to the sewer.

After a bed is steam-desorbed, the bed is dried and cooled with ambient air. The ambient air is pulled through the open treated air exhaust valve, through the bed in reverse flow, through the condenser/cyclone, and back to the inlet of the on-line adsorbers. This cooling/drying mechanism allows residual solvent in the bed to be removed, condensed, and routed to the distillation section. At the end of this cooldown period, the regenerated bed is placed into standby service; i.e., it is closed off to SLA and steam flow.

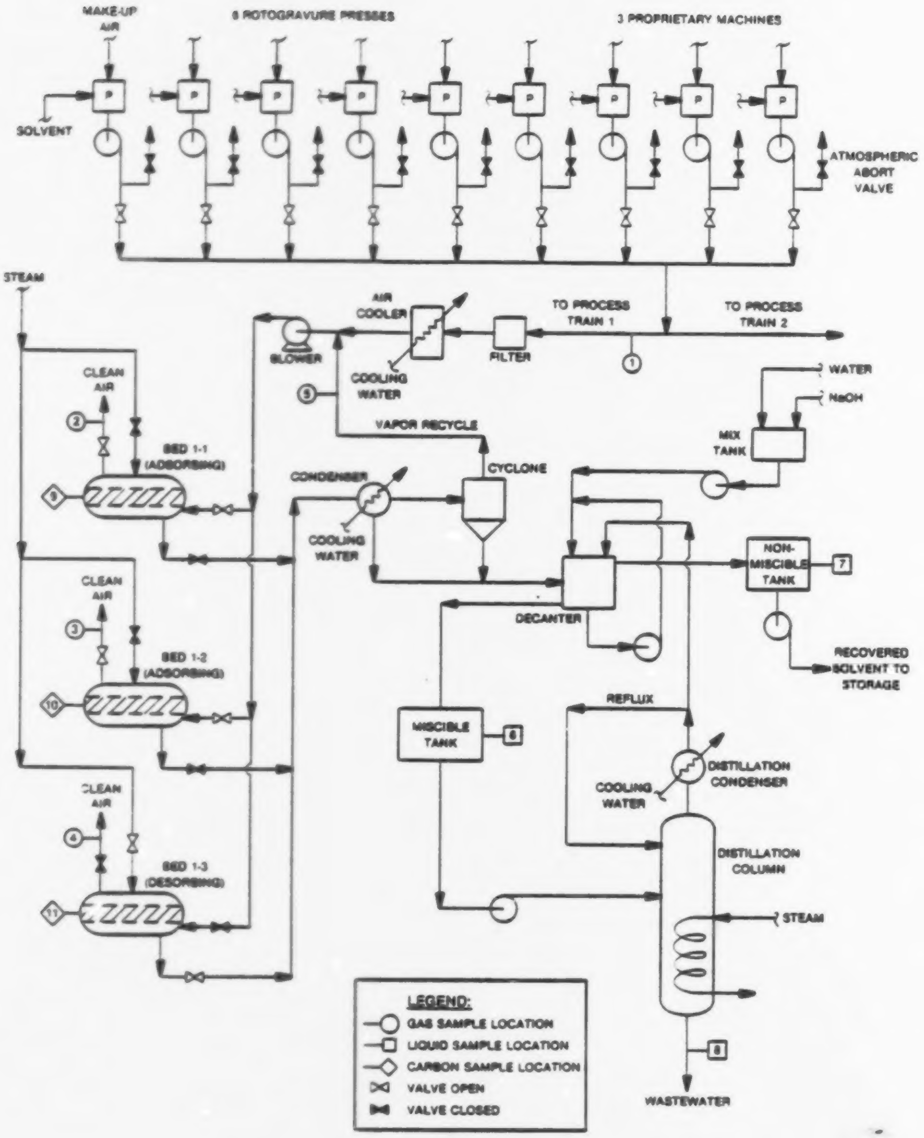
MAKE-UP AIR
6 ROTOGRAVURE PRESSES
3 PROPRIETARY MACHINES
SOLVENT
P
ATMOSPHERIC ABORT VALVE
STEAM
AIR COOLER
TO PROCESS TRAIN 1
TO PROCESS TRAIN 2
BLOWER
FILTER
COOLING WATER
1
5
WATER
NaOH
CLEAN AIR
2
VAPOR RECYCLE
BED 1-1 (ADSORBING)
MIX TANK
9
CYCLONE
CONDENSER
COOLING WATER
NON-MISCIBLE TANK
7
DECANTER
CLEAN AIR
3
BED 1-2 (ADSORBING)
RECOVERED SOLVENT TO STORAGE
10
REFLUX
MISCIBLE TANK
6
DISTILLATION CONDENSER
COOLING WATER
CLEAN AIR
4
DISTILLATION COLUMN
BED 1-3 (DESORBING)
11
STEAM
LEGEND:
GAS SAMPLE LOCATION
LIQUID SAMPLE LOCATION
CARBON SAMPLE LOCATION
VALVE OPEN
VALVE CLOSED
8
WASTEWATER

Figure 11-1. Plant 6 solvent recovery system.

The sequencing of the adsorption/regeneration modes of the three beds in each process train is controlled by an infrared (IR) hydrocarbon exhaust gas analyzer and a timer. Each bed typically remains in adsorption service from six to twelve hours, depending on the inlet solvent concentrations. When the exhaust solvent concentration exceeds a breakthrough setpoint (approximately 30 ppmv as toluene/IPAC), the IR analyzer generates a signal to close off the bed to SLA flow and open it up to steam flow. The spent bed is desorbed for 30 minutes, cooled down for 34 minutes, and placed into standby service until the next bed in sequence is ready for regeneration, typically several hours later.

The bed cycle sequencing during the original test period in 1982 and the repeat test period in 1983 is shown below (only the sequencing for three beds, i.e., one process train, is shown):

Segment	Bed 1-1	Bed 1-2	Bed 1-3	Time (Original)	Time (Repeat)
1	Ads	Des	Ads	30 min.	30 min.
2	Ads	Cool	Ads	34 min.	34 min.
3	Ads	Std	Ads	115-215 min.	130-295 min.
4	Ads	Ads	Des	30 min.	30 min.
5	Ads	Ads	Cool	34 min.	34 min.
6	Ads	Ads	Std	115-210 min.	130-295 min.
7	Des	Ads	Ads	30 min.	30 min.
8	Cool	Ads	Ads	34 min.	34 min.
9	Std	Ads	Ads	115-210 min.	130-295 min.

The solvent recovery system at Plant 6 is well instrumented. System operation is mostly automatic and features a programmable controller for remote control, operation and monitoring. The following instrumentation is available:

- a detailed flow diagram mounted on an operator's control panel, indicating the status of various components of the system (which beds are on-line, desorbing, cooling, or on standby; which pumps are operating; various warning lights and alarms for upset conditions, etc.);

- a recorder indicating total system inlet SLA flow rate;

- a recorder indicating the percentage of lower flammability limit (LFL) of the inlet SLA as measured by a catalytic-type detector;

- a recorder indicating exhaust solvent concentrations from the beds in ech process train as measured by the IR analyzers;

- a recorder indicating total steam flow; and

- a multipoint temperature recorder indicating temperatures of the carbon beds, cooling water supply, cooling water return, air cooler inlet, and ambient air.

With the exception of the steam flow meter, all process instrumentation was operational during the time of the testing.

TEST RESULTS

Testing of the Plant 6 carbon adsorption system focused on the characterization of: (1) general operating parameters; (2) VOC control performance; and (3) carbon, solvent and wastewater properties. Results of these characterizations are presented in this section.

General Operating Parameters

General operating conditions for the Plant 6 carbon adsorption system during the original and repeat test periods are presented in Table 11-2. The data are categorized as adsorption and regeneration mode data.

The original and repeat test results indicated several differences in adsorption mode operation. Adsorption mode length during the original testing averaged 470 minutes compared to 560 minutes for the repeat testing. The longer adsorption times during the repeat testing may be attributed to the following factors: (1) lower inlet solvent loadings (the length of the adsorption period was controled by a solvent breakthrough analyzer) and (2) greater adsorption capacity of the carbon due to cooler and drier operating conditions (reflecting ambient conditions).

The regeneration mode data for the Plant 6 system show similar performance for both test periods. The steam/recovered solvent ratio was exceptionally low for both test periods as compared with those of other systems. The steam/solvent ratios, ranging from 0.8 to 1.0 kg/kg (0.8 to 1.0 lb/lb), were calculated based on plant chart recordings of steam flow rate and estimates of solvent recovery rates (inlet solvent - stack losses - wastewater losses). Long-term plant data indicated average steam/solvent ratios of 1.4, based on steam flow rate data and measurements of liquid solvent recovery levels.

VOC Control Efficiency Performance

Summarized VOC control efficiency data for the carbon adsorption system at Plant 6 are presented in Table 11-3. As shown by the summary data, inlet VOC concentrations averaged less than 1,000 ppmv, with average outlet concentrations approximating 20 ppmv during both test periods. VOC control efficiencies averaged about 98 percent for both test periods, with no degradation

TABLE 11-2. GENERAL OPERATING DATA FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 6

Operating Parameter	Operating Conditions (Process Train 1 Only)[a]	
	Original Test - August, 1982	Repeat Test - November, 1983
Adsorption Mode		
Solvent type	Toluene/IPAC	Toluene/IPAC
Mode length	470 min	560 min
Inlet SLA flow rate	15.8 Nm^3/sec (33,400 scfm)	16.0 Nm^3/sec (33,900 scfm)
SLA superficial velocity	0.26 m/sec (51 ft/min)	0.26 m/sec (52 ft/min)
Bed residence time	3.6 sec	3.5 sec
SLA temperature drop across air cooler	14°C (25°F)	4°C (8°F)
Inlet SLA temperature (after air cooler)	33°C (91°F)	19°C (67°F)
Inlet SLA relative humidity	44%	35%
Carbon bed pressure drop	Bed 1-1 - 0.92 kPa (3.7 in. H_2O)	Bed 1-1 - 0.97 kPa (3.9 in. H_2O)
	Bed 1-2 - 1.1 kPa (4.4 in. H_2O)	Bed 1-2 - 1.0 kPa (4.2 in. H_2O)
	Bed 1-3 - 1.1 kPa (4.4 in. H_2O)	Bed 1-3 - 1.0 kPa (4.2 in. H_2O)
Outlet air flow rate	Bed 1-1 - 8.6 Nm^3/sec (18,300 scfm)	9.1 Nm^3/sec (19,200 scfm)
	Bed 1-2 - 8.7 Nm^3/sec (18,400 scfm)	8.7 Nm^3/sec (18,400 scfm)
	Bed 1-3 - 8.4 Nm^3/sec (17,700 scfm)	9.2 Nm^3/sec (19,600 scfm)
Outlet air temperature	32°C (90°F)	24°C (75°F)
Outlet air relative humidity	65%	41%
Regeneration Mode		
Desorption period length	30 min	30 min
Cooldown period length	34 min	34 min
Standby period length	115 - 215 min	130 - 295 min
Steam flow rate (per bed desorption)	1,540 kg/hr (3,400 lb/hr)[b]	1,500 kg/hr (3,300 lb/hr)[b]
Steam/recovered solvent ratio	1.0 kg/kg (1.0 lb/lb)[c]	0.8 kg/kg (0.8 lb/lb)[c]
Steam pressure	520 kPa (60 psig)	520 kPa (60 psig)
Steam temperature	153°C (307°F)	153°C (307°F)
Wastewater flow rate	44 kg/hr (96 lb/hr)[d]	36 kg/hr (79 lb/hr)[d]

[a] Average values are presented.

[b] Based on plant chart recordings.

[c] Based on measured VOC data and plant steam flow data.

[d] Estimated from steam flow rate and assumes continuous operation of the distillation unit.

TABLE 11-3. VOC CONTROL EFFICIENCY DATA FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 6

	Inlet VOC Loading		Outlet VOC Emissions		VOC Control Efficiency, %[b,c]
	Concentration, ppmv[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	Concentration, ppmv,[a,b]	Mass Rate, kg/hr (lb/hr)[a,b]	
Original Test - August, 1982					
Bed 1-1	995	114 (251)	21	2.6 (5.8)	97.7
Bed 1-2	844	101 (222)	21	2.7 (5.9)	97.3
Bed 1-3	874	102 (224)	20	2.6 (5.8)	97.5
Repeat Test - November, 1983					
Bed 1-1	798	96.7 (213)	15	2.0 (4.4)	97.9
Bed 1-2	1,020	132 (290)	18	2.5 (5.4)	98.1
Bed 1-3	724	75.4 (166)	15	1.9 (4.2)	97.5

[a] As a 50/50 mole percent mixture of toluene and IPAC.

[b] Average values are presented.

[c] Efficiency expressed on a "system" basis.

in performance observed during the repeat testing. The carbon service life during the original and repeat testing was approximately 0.2 and 1.6 years, respectively.

The similarity in VOC control performance during both test periods is further illustrated by the example VOC concentration profiles in Figure 11-2. The outlet VOC curves, shown for Bed 1-1, resemble typical solvent breakthrough curves. VOC profiles for Bed 1-2 and Bed 1-3 show similar trends for both test periods.

Periodic gas chromatographic (GC) analysis of the inlet SLA indicated the presence of toluene and IPAC in concentrations closely approximating a 50/50 volume percent mixture, which was consistent with the plant coating formulation. Furthermore, the sum of the toluene and IPAC concentrations closely approximated the measured THC concentrations. Finally, GC analysis of the inlet SLA indicated the presence of unburned methane from the natural gas-fired drying ovens. Relative to the solvent concentrations, the inlet methane concentrations were relatively low, nominally 50 ppmv.

GC analysis of the adsorber exhaust air resulted in two significant findings: (1) solvent components were selectively displaced from the carbon bed during adsorption and (2) unburned methane from the gas-fired coating ovens passed through the bed unadsorbed and represented the majority of the measured outlet THC emissions.

GC analysis of the adsorber exhaust air indicted that the solvent components were selectively displaced in the carbon bed during absorption. Figure 11-3 shows the selective displacement of various solvent components through a typical adsorption cycle. As shown, unidentified minor light solvent components began breaking through the bed about four hours into the eight-hour cycle (these "other" compounds were arbitrarily expressed on a 50/50 volume percent toluene/IPAC basis). IPAC began breaking through about

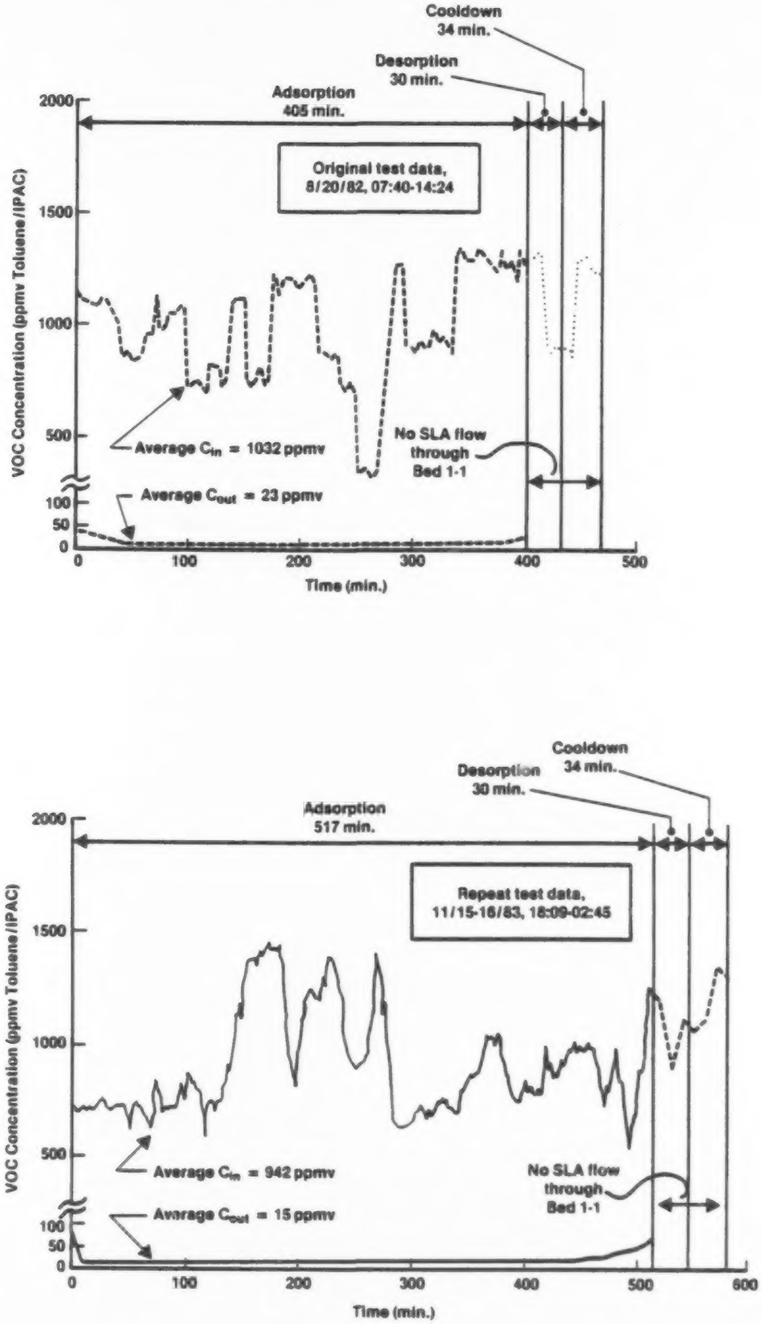

Figure 11-2. Plant 6 VOC concentration profiles - Bed 1-1.

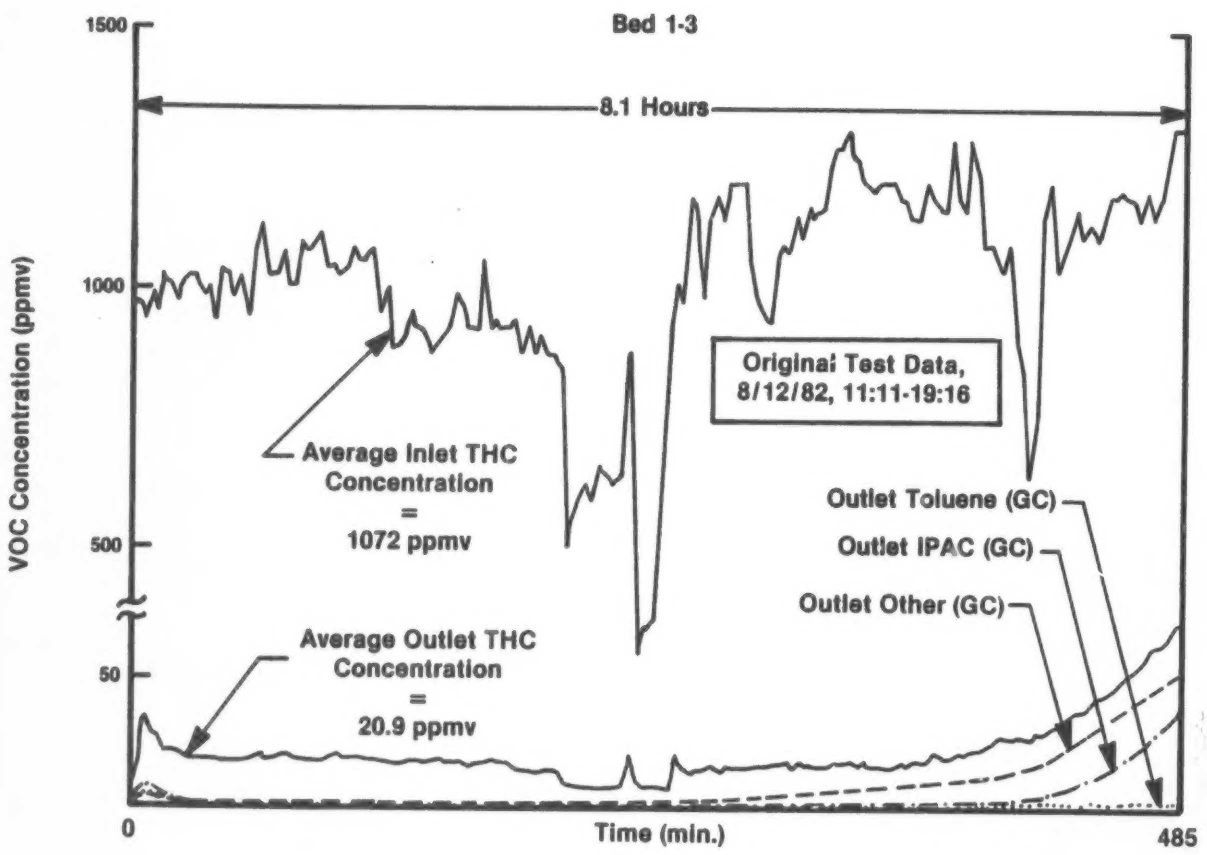

Figure 11-3. Plant 6 THC and speciated concentrations profiles - Bed 1-3.

six hours into the cycle, reaching a maximum of 40 ppmv at cycle completion. The heavier toluene solvent, which displaced the lighter solvents from the bed, never broke through at significant levels, measuring only 2 ppmv at cycle's end.

The concentration profiles also show that measured THC concentrations significantly exceeded the GC-measured solvent concentrations through most of the cycle. This result was due to the presence of unburned methane in the exhaust air, which represented most of the measured THC emissions. The significant contribution of methane to the measured outlet THC concentrations indicates that the measured control efficiencies, as expressed on a THC basis, understate the ability of the carbon adsorber to remove solvent vapors. (Plant 6 was the only tested plant to use direct-fired drying ovens, so the discrepancy between solvent control efficiency and THC control efficiency due to "methane interference" was limited to this plant. Exclusion of the contribution of methane to the measured inlet and outlet THC concentrations resulted in "adjusted" THC control efficiencies approximately 1.0 percentage point higher than the values presented in Table 11-3.)

Carbon, Solvent and Wastewater Characteristics

Results of the carbon, solvent and wastewater analyses for the Plant 6 solvent recovery system are summarized in Table 11-4 and discussed below.

As shown by the CCl_4 activity and volatiles content data, the coal-based carbon in service at Plant 6 showed similar values during the original and repeat test periods (service life of 0.2 and 1.6 years, respectively). In addition, characteristics of the bed carbon were not significantly different from those of virgin carbon, even during the repeat test period.

Analysis of virgin solvent samples indicated approximately 90 and 100 percent purity levels for toluene and IPAC, respectively. Analysis of recovered solvent samples confirmed the presence of toluene and IPAC in approximately equal, i.e., 50/50, portions.

TABLE 11-4. CHARACTERISTICS OF CARBON, SOLVENT, AND WASTEWATER FOR THE CARBON ADSORPTION SYSTEM AT FLEXIBLE PACKAGING PLANT 6

Parameter	Original Test Period August, 1982[a]						Repeat Test Period November, 1983[a]		
	Bed 1-1	Bed 1-2	Bed 1-3				Bed 1-3		
Carbon Analysis[b]	Middle	Middle	Influent	Middle	Effluent	Virgin	Influent	Middle	Effluent
Service life	0.2 yr	0.2 yr	0.2 yr	0.2 yr	0.2 yr	NA	1.6 yr	1.6 yr	1.6 yr
CCl_4 activity, %	41	26	27	33	64	57	38	41	53
CCl_4 retentivity, %	7	6	6	11	34	33	10	11	18
Volatiles, %	NM	NM	22	19	5	1	16	12	9
Surface area, m^2/g	NM	NM	NM	NM	NM	938	NM	NM	NM
Moisture, %	NM	NM	2	6	24	5	9	11	17
Particle size, mm[c]	NM	NM	3.3	3.7	3.5	3.6	3.5	NM	NM
Solvent Analysis	Recovered Toluene		Virgin Toluene		Virgin IPAC			Recovered Solvent	
Toluene, wt %	46.1		88.1		NM			48.5	
IPAC, wt %	49.1		NM		99.6			43.2	
n-Propyl acetate, wt %	4.1		NM		NM			6.0	
Other, wt %[d]	NM		11.9		0.4			1.8	
Water, wt %	0.8		<0.1		<0.1			0.5	
Wastewater Analysis									
Toluene, ppm (wt)		63						5	
IPAC, ppm (wt)		1,700						92	
n-Propyl acetate, ppm (wt)		89						NM	
Other, ppm (wt)[d]		24,000						2,900	

NA = Not applicable NM = Not measured

[a] Average values are presented.

[b] Carbon samples were collected after bed desorption

[c] Sieve size through which 50% of the carbon sample weight passed.

[d] As hexane.

Analysis of process wastewater indicated organic concentrations ranging from 3,000 to nominally 30,000 ppm. Ethanol and isopropanol, minor constituents of the coating formulation, constituted the bulk of the organic loading in the wastewater. The high discharge of these alcohols in the wastewater was apparently due to hydrolysis of the acetates in the distillation process and the high solubility of the alcohols in water. The average organic loading of the wastewater represented approximately 0.1 to 1 percent of the total solvent processed by the solvent recovery unit.

COST DATA

Cost data for the Plant 6 solvent recovery system are presented in this section. Included is a list of equipment represented by the cost data, followed by estimated capital and annualized costs.

Equipment List for Costing

The following major equipment items are included within the cost data supplied for the Plant 6 solvent recovery system:

- SLA transport equipment, including SLA blowers and ductwork from the ovens;
- SLA preconditioning equipment, including the filters and air coolers;
- solvent adsorption equipment, consisting of the adsorber vessels and related equipment; and,
- solvent separation equipment, consisting of the distillation section of the solvent recovery unit.

Specifically excluded from the cost data are equipment items associated with solvent/coating blending, surface coating, web drying (ovens), and solvent storage.

Capital Costs

Capital costs for the Plant 6 solvent recovery system are presented in Table 11-5. Costs are expressed in late 1983 dollars. As shown, the total estimated capital cost is $2,685,000, which corresponds to $72,000/Nm3/sec ($34/scfm).

Annualized Costs

Estimted annualized costs for the Plant 6 system, in 1983 dollars, are presented in Table 11-6. As shown, total annualized costs approximate $839,000 per year, with capital recovery, labor and indirect costs representing the major cost components. The total annualized cost corresponds to a unit cost of $0.28 kg ($0.13/lb) of recovered solvent.

TABLE 11-5. CAPITAL COSTS FOR THE SOLVENT RECOVERY SYSTEM AT FLEXIBLE PACKAGING PLANT 6[a]

DIRECT COSTS	
• Delivered equipment	\$ 2,257,000
• Installation materials (ducting, piping, foundations, buildings, electrical, instrumentation, insulation, painting, tankage, etc.)	Included above
• Installation labor	Included above
TOTAL DIRECT COSTS (TDC)	\$ 2,257,000
INDIRECT COSTS	
• Engineering and supervision	\$ 55,000
• Miscellaneous construction expenses	193,000
• Contractor's fees	Included above
• Contingencies	148,000
TOTAL INDIRECT COSTS (TIC)	\$ 396,000
OTHER COSTS	
• Interest during construction	\$ 0[b]
• Startup	32,000
• Other	0[b]
TOTAL OTHER COSTS (TOC)	\$ 32,000
TOTAL CAPITAL COSTS (TCC = TDC + TIC + TOC)	\$ 2,685,000
RELATIVE CAPITAL COSTS	
• TCC/design SLA flow rate	\$ 72,000/Nm^3/sec (\$34/scfm)
• TCC/design carbon charge	\$ 32/kg (\$14/lb)

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[a] All cost figures, unless otherwise noted, were obtained by scaling plant-supplied data to a late 1983 capital cost basis. Scaling factors were obtained from the Chemical Engineering Plant Cost Index; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

TABLE 11-6. ANNUALIZED COSTS FOR THE SOLVENT RECOVERY SYSTEM AT FLEXIBLE PACKAGING PLANT 6[a]

DIRECT COSTS	
• Labor	
--operating	$ 97,000
--maintenance	9,000
--laboratory	14,000
--supervisory	26,000
• Maintenance materials	37,000
• Activated carbon	15,000[b]
• Utilities	
--electricity	40,000
--steam	38,000
--cooling water	22,000
--chilled water	0
TOTAL DIRECT COSTS (TDC)	$ 299,000/yr
INDIRECT COSTS	
• Capital recovery[c]	$ 438,000[b]
• Labor and plant overhead	9,000[b]
• General and administrative	27,000[b]
• Insurance and property tax	66,000
TOTAL INDIRECT COSTS (TIC)	$ 540,000/yr
TOTAL ANNUALIZED COSTS (TAC = TDC + TIC)	$ 839,000/yr
RELATIVE ANNUALIZED COSTS	
• TAC/actual annual SLA throughput	$ 1.0/10^3Nm^3 ($0.03/$10^3$scf)[d]
• TAC/actual annual solvent recovery	$ 0.28/kg ($0.13/lb)[d]

[a] All cost figures, unless otherwise noted, were obtained by multiplying plant-supplied unit costs (e.g., $/man-hour) by measured or plant-supplied operating rates (e.g., man-hours/week). Costs are expressed on a late 1983 basis; original plant-supplied data are presented in Appendix A. Totals may not add due to rounding.

[b] Estimated.

[c] Capital recovery = $\text{TCC} \times \frac{(1+i)^n i}{(1+i)^n - 1}$

where
TCC = total capital cost
i = interest rate @ 0.10
n = equipment life @ 10 years

[d] Based upon original test data.

SECTION 12

COMPARISON OF PERFORMANCE RESULTS OF PLANTS 1 - 6

The current program was conducted to fulfill the program objectives, as introduced in Section 1: (1) to determine the effects of carbon service life on long-term system performance, (2) to test the adsorbers under a variety of conditions, and (3) to select a model that represents adsorption and to compare field data to the model's prediction. This section compares the program results on a collective basis. Specifically, the subsections entitled "Design and Cost Comparisons" and "Systems Performance Comparisons" compare the design specifications and operating performance of the tested systems. The subsection entitled "Carbon Life" discusses the effects of carbon life on long-term system performance.

DESIGN AND COST COMPARISONS

Two carbon adsorption systems were tested in each of the following surface coating industries: rubberized fabric, magnetic tape, and flexible packaging. Design specifications and cost information for these adsorption systems are compared in table 12-1.

As shown, the tested plants represent a wide range of designs. For example, the adsorption systems at the rubberized fabric and flexible packaging plants feature horizontal carbon beds, although SLA flow direction through the beds differs (downward for rubberized fabric Plants 1 and 5 and upward for flexible packaging Plants 4 and 6). Conversely, the magnetic tape plants feature adsorption systems with annular carbon beds although, again, SLA flow

TABLE 12-1. COMPARISON OF DESIGN AND COST INFORMATION -- PLANT 1-6

Industry	Rubberized Fabric		Magnetic Tape		Flexible Packaging	
PLANT	1	5	2	3	4	6
DESIGN SPECIFICATIONS						
Bed configuration	horizontal	horizontal	annular	annular	horizontal	horizontal
Number of beds	2	3	3	6^{a}	3	6
SLA flow direction	downward	downward	inward	outward	upward	upward
SLA flow rate, Nm^3/sec (scfm)	5.30 (11,200)	5.25 (11,100)	6.01 (12,700)	10.9 (23,000)	10.4 (22,000)	37.8 (80,000)
Relative flow rate, Nm^3/sec-kg carbon (scfm/lb)^{b}	0.0012 (1.1)	0.0015 (1.5)	0.0026 (2.5)	0.0012 (1.1)	0.0017 (1.6)	0.00068 (0.65)
Superficial velocity, m/sec (ft/min)	0.44 (87)	0.47 (92)	0.31 (61)	0.36 (70)	0.44 (87)	0.31 (61)
Inlet SLA temperature, °C (°F)	35 (95)	38 (100)	32 (90)	29 (85)	35 (95)	49 (120)^{c}
Solvent type	MEK/toluene	toluene	THF/toluene	THF/toluene/MEK/MIBK/cyclohexanone	hexane	toluene/IPAC
Liquid molar volume, cm^3/g-mole^{d}	96	106	93	93	126	110
Inlet solvent concentration, ppmv	4,050	1,260	850	2,000	4,340	670
Relative solvent loading, kg solvent/kg carbon/hr (lb/lb/hr)^{b}	0.058 (0.058)	0.027 (0.027)	0.028 (0.028)	0.031 (0.031)	0.097 (0.097)	0.0066 (0.0066)
VOC control efficiency, %	95	97	92	NS	96	97
SOLVENT RECOVERY SYSTEM COSTS						
Total capital cost, 1983 $10^3	622	267	650	1,800	1,334	2,685
Relative capital cost, $10^3/Nm^3/sec ($/scfm)	118 (56)	51 (24)	108 (51)	173 (82)	129 (61)	72 (34)
Total annualized cost, 1983 10^{3\,e}$	262	125	325	1,430	494	839
Relative annualized cost, $/kg recovered solvent ($/lb)	0.53 (0.24)	0.19 (0.09)	0.61 (0.28)	0.66 (0.30)	0.51 (0.23)	0.28 (0.13)

NS = Not specified

[a] Only 4 beds were in service during the test period.

[b] Refers to the SLA and solvent loadings to the carbon in the on-line (adsorbing) carbon beds.

[c] Maximum.

[d] At 20°C.

[e] Costs are not normalized and reflect actual plant to plant differences in labor and utility costs.

direction through the bed differs (inward for Plant 2 and outward for Plant 3). The number of carbon beds also varies considerably, from two to six.

Design specifications related to SLA conditions show that the adsorption systems at the two rubberized fabric plants were the smallest units tested, with an average design SLA flow rate of nominally 5.3 Nm^3/sec (11,000 scfm). The magnetic tape plant adsorption systems range from 6.0 to 10.9 Nm^3/sec (13,000 to 23,000 scfm) in size, with the flexible packaging plant adsorption systems being the largest units tested, ranging from 10.4 to 37.8 Nm^3/sec (22,000 to 80,000 scfm) in size.

The relative SLA flow rates, as compared to the bed carbon capacity, average approximately 0.0015 Nm^3/sec-kg carbon (1.5 scfm/lb carbon) for the six tested systems. Four of the plants have systems with relative SLA flow rates closely approximating this average value, but the designs for the adsorption systems at Plants 2 and 6 deviate significantly from the mean. The Plant 6 system design features a relatively conservative 0.00069 Nm^3/sec-kg carbon (0.65 scfm/lb carbon), whereas the Plant 2 design is characterized by a relatively high 0.0026 Nm^3/sec-kg (2.5 scfm/lb).

With the exception of the conservative Plant 6 design, the horizontal bed systems feature average design superficial bed velocities of 0.45 m/sec (89 ft/min). The thin-bed design of the annular bed systems feature lower velocities, nominally 0.33 m/sec (65 ft/min), to achieve adequate bed residence time.

Design solvent types vary considerably, although toluene is a major design component at five of the six plants. Liquid molar volumes of the design solvent formulations range from 93 to 126 cm^3/g-mole, with the lightest and heaviest solvent formulations used at the magnetic tape and flexible packaging plants, respectively. The six designs are characterized by significant differences in inlet solvent loadings, with inlet concentrations ranging from less than 1,000 ppmv to over 4,000 ppmv. On a carbon basis, design solvent loadings vary over an order of magnitude, from 0.0066 to 0.097 kg solvent/kg carbon (0.0066 to 0.097 lb solvent/lb carbon).

Several results are evident from the cost information presented in Table 12-1. Total estimated capital costs, in 1983 dollars, range from less than $700,000 for the three smallest units (Plants 1, 2 and 5) to over $2,600,000 for the largest unit (Plant 6). On a relative basis, capital costs range from $51,000 to $173,000 per Nm3/sec ($24 to $82 per scfm). The solvent recovery system at Plant 3 has the highest capital cost in this range. Plant personnel indicate that excessive capital costs were incurred due to the complexity of the distillation unit and because of significant problems associated with startup (including total replacement of major equipment items). Conversely, the lowest capital cost in this range is represented by the relatively small Plant 5 solvent recovery unit. Plant personnel attribute its low capital cost to its simple design and the competitiveness of the initial quote. Also of note is the economy of scale represented by the low relative capital cost of the Plant 6 system, despite the incorporation of conservative design principles into this unit.

Annualized costs for the solvent recovery units at Plants 1, 2, 3 and 4 are similar, ranging from $0.51 to $0.66 per kg ($0.23 to $0.30 per lb) of recovered solvent. Plant 6 features a relatively low $0.28 per kg ($0.13 per lb) of recovered solvent, due primarily to low total costs for utilities (steam, electricity, and cooling water). The Plant 5 system also features a low annualized cost, approximating $0.19 per kg($0.09 per lb) of recovered solvent, due primarily to low labor and capital recovery costs.

SYSTEM PERFORMANCE COMPARISONS

Performance parameters for the six tested carbon adsorption systems are compared in Table 12-2. All six plants were originally tested in early 1982. During these tests, data were taken to characterize the VOC removal efficiency

TABLE 12-2. COMPARISON OF SYSTEM PERFORMANCE -- PLANTS 1-6

Industry	Rubberized Fabric			Magnetic Tape			Flexible Packaging			
PLANT	1	5		2		3	4		6	
GENERAL OPERATING PARAMETERS	Original Test	Original Test	Repeat Test	Original Test	Repeat Test	Original Test	Original Test	Repeat Test	Original Test	Repeat Test
Adsorption mode length, min.	95[a]	150	200	64	64	47	120	90	470[a]	560[a]
SLA flow rate, Nm^3/sec (scfm)	5.4 (11,400)	4.3 (9,100)	3.7 (7,800)	4.6 (9,800)	4.5 (9,500)	9.4 (19,800)[b]	8.3 (17,700)	10.7 (22,600)	15.8 (33,400)[c]	16.0 (33,900)[c]
Actual SLA/Design SLA, %	102	82	70	77	75	129	80	103	84	85
Inlet SLA temperature, °C (°F)	34 (94)	40 (104)	56 (132)	23 (74)	32 (90)	27 (81)	32 (89)	22 (72)	33 (91)	19 (67)
Desorption mode length, min.	55	50	40	32	32	35	25	25	30	30
Steam/recovered solvent, kg/kg (lb/lb)	20 (20)	8.2 (8.2)	15 (15)	5.2 (5.2)	6.5 (6.5)	6.0 (6.0)	4.6 (4.6)	11 (11)	1.0 (1.0)	0.8 (0.8)
VOC CONTROL PARAMETERS										
Solvent type	MEK	toluene	toluene	THF/ toluene[d]	THF/ toluene[d]	THF/toluene/ MEK/MIBK/cyclohexanone	hexane	hexane	toluene/ IPAC	toluene/ IPAC
Inlet solvent concentration, ppmv	2,190	1,940	896	1,470	1,140	3,220	1,260[e]	940[e]	904	847
VOC control efficiency, %	84.9	97.6	80.5	99.7	95.2	94.7	99.0[e]	46.7[e]	97.5	97.9

[a] Cycle timing controlled by exhaust gas (breakthrough) hydrocarbon analyzer.

[b] Flow rate measured when 4 of the 6 beds were in service (2 beds were on permanent standby).

[c] Process Train 1 conditions (total system capacity was twice that of Process Train 1).

[d] Original THF/toluene percentages were 50/50; repeat test percentages were 75/25.

[e] Measurements made at common inlet/common outlet.

of the carbon bed system and also to characterize the conditions of the carbon. Four of the six plants were tested again approximately 18 to 22 months later. The same tests were performed in these repeat tests as were performed in the original tests. A comparison of the changes in performance was made in an attempt to assess the effects of long-term carbon degradation. In general, the data in Table 12-2 indicate significant differences in performance from plant to plant and from test period to test period. However, these differences were not always attributable to carbon degradation.

Average adsorption times per bed for the six tested systems showed significant variation, ranging from 64 minutes to 560 minutes. Differences in adsorption times between the original and repeat testing were also noted at Plants 4, 5 and 6. The timer-controlled adsorption mode at Plant 4 was shortened prior to the repeat testing in an attempt to improve solvent recovery efficiency. In contrast. the adsorption time during the repeat test period at Plant 5 was greater than during the original test period in response to lower coating production rates. The analyzer-controlled adsorption time at Plant 6 was greater during the repeat test period due to lower solvent loadings and subsequently less rapid solvent breakthrough.

Measured SLA flow rates for the six tested adsorption systems ranged from 70 to almost 130 percent of the design flow rates. Also, significant variation in SLA flow rate was measured during the two test periods, except at Plants 2 and 6 (both systems processed SLA at levels 75 to 85 percent of capacity).

With the exception of the Plant 5 system, the carbon adsorption systems treated SLA streams at temperatures recommended for solvent recovery applications, i.e., less than approximately 38°C (100°F). However, adsorption temperatures were greater than this for the Plant 5 system, especially during the repeat test period, when inlet SLA temperatures averaged 56°C (132°F).

Differences in performance were also measured with regard to bed regeneration characteristics. Steaming periods ranged from 25 to 55 minutes, with the mean period equal to approximately 30 minutes. Steam/recovered solvent ratios varied considerably, ranging from less than 1.0 kg/kg (1.0 lb/lb) at Plant 6 to 20 kg/kg (20 lb/lb) at Plant 1. Steam temperature varied from 110 to 150°C (230 to 300°F). Actual bed temperatures during regeneration were not measured during the tests.

The inlet VOC measurements for the six tested systems varied between plants and between test periods. Average inlet solvent concentrations ranged from nominally 1,000 ppmv to 3,000 ppmv. These solvent loadings correspond to approximately 5 to 20 percent of the lower explosive limits (LELs) for these compounds. For the four systems that were subjected to repeat testing (Plants 2, 4, 5 and 6), average inlet solvent concentrations were generally lower during the repeat test period. In all cases, the lower inlet solvent concentrations corresponded to lower average coating production rates.

The average VOC control efficiency data presented in Table 12-2 indicate that, with the exception of the Plant 1 system, all tested adsorption systems were capable of achieving efficiencies of 95 percent or greater. For three of the four systems retested, a marked degradation in performance was measured. However, in most cases, carbon service life did not appear to be the primary factor responsible for the decreased performance. Rather, mechanical malfunctioning of the system appears to have been responsible for the lower performance levels.

CARBON LIFE

Carbon life is defined as the expected useful life of an activated carbon based on VOC removal performance. The end of a carbon lifetime is normally marked by a reduction in the VOC removal efficiency or by significant changes in the system operation to maintain a certain VOC removal efficiency. The carbon life for typical fixed-bed steam-regenerated carbon adsorption systems ranges from a few months to several years. Of the plants tested in this study, one plant (Plant 3) routinely changed carbon every nine months, while another plant (Plant 5) was experiencing acceptable VOC removal performance after six years of carbon life. Useful carbon life is difficult to predict but generally is related to degradation of the carbon by reduced activity of the carbon surface and/or by plugging of the micropore structure.

There are no established methods to accurately predict or estimate the carbon life of a particular carbon bed system; however, estimates of carbon life can sometimes be made from bench-scale, pilot plant, and full-scale unit operating histories. Also, carbon life can be qualitatively discussed with regard to fouling and deactivation potential of contaminants in the SLA gas stream. Therefore, for this study, the following long-term test results were investigated to evaluate the relationship between carbon life and system performance for full-scale units: (1) reductions in total system VOC removal capability and (2) changes in the characteristics of the activated carbons. The next subsections discuss the results of each of these examinations.

Carbon Life and Reduction in VOC Removal

Four plants (Plants 2, 4, 5 and 6) were performance tested at two separate time periods, 18 to 22 months apart. The tests were designed to define potential reductions in the systems' VOC removal capabilities as the carbon service life increased. Of the systems tested, Plants 4 and 6 appeared to have suffered no measurable reduction in performance level (discounting solvent losses due to mechanical valve malfunctions at Plant 4). The Plant 5 carbon adsorption system was plagued with a variety of mechanical and operating problems, such that interpretation and comparison of the two data sets was difficult. Only the Plant 2 testing provided data that appeared to show VOC control efficiency reductions caused by carbon degradation.

The overall system data for Plant 4, presented earlier in Table 12-2, indicate a considerable decrease in VOC control performance, from 99 percent to 47 percent. However, the majority of the performance degradation resulted from leaking steam outlet valves during the repeat testing. Improper steam valve closure allowed steam/solvent vapors from a regenerating bed to leak into the on-line beds, significantly affecting adsorption efficiency. Other than the solvent losses incurred by the valve leaks, however, the carbon beds appeared to operate similarly during the two test periods. In fact, the repeat testing indicated baseline solvent emission levels approximately equal to those measured during the original testing, with no significant solvent breakthrough trends detected. Furthermore, gas-phase VOC analyses performed by the plant after the faulty valves were replaced (immediately after the repeat test period) indicated VOC removal levels approximating those measured during the original testing, i.e., 99 percent. These data suggest that the Plant 4 carbon has a relatively long useful service life, exceeding five years.

Plant 6 VOC control efficiencies were similar during the original and repeat test periods, averaging almost 98 percent. Several factors may be responsible for the lack of change in performance. First, the service time of the bed carbon was relatively short (0.2 to 1.6 years) relative to those of the other tested systems (2.0 to 6.5 years). Second, operating conditions were much more similar during the two test periods than for the other tested systems. Finally, conservative design principles are incorporated into the Plant 6 carbon adsorption system. In particular, the solvent mass loading and SLA flow rate per bed carbon volume are very low, relative to the other systems. As a result, the potential for carbon deactivation is reduced, by distribution of the adsorption duty to a greater mass of carbon. The short service time of the carbon charge in place during the testing and the lack of difference in performance prevent the accurate estimation of useful carbon life for the Plant 6 system. However, its conservative design and lack of performance degradation between the two test periods suggests that the useful life of the carbon is relatively long, perhaps in excess of five years.

Plant 5 VOC control performance levels also showed a significant decrease from the original to the repeat test period, from 98 percent to 80 percent. However, the degradation in VOC control efficiency was primarily due to mechanical problems, in particular, a leaking steam valve and channeling in Bed B (these were confirmed and repaired during a system shutdown several weeks after the repeat testing was performed). Variations in cycle timing, higher operating temperatures, lower inlet solvent concentrations, and increased carbon age appeared to account for a smaller portion of the performance decrease. The operating problems and other process variations prevent the accurate comparison of the data sets. However, one major result is apparent; i.e., that the useful carbon service life for the Plant 5 system is at least five years, based upon VOC removal levels of 98 percent measured during the original test period.

As indicated earlier in Table 12-2, the Plant 2 system showed VOC control performance degradation from 99+ percent (original testing) to 95 percent (repeat testing). Several operating factors may have contributed to this reduction in performance, including solvent formulation changes and changes in adsorption and desorption temperatures. However, these changes would not be expected to be the primary causes for the significant performance decrease measured. Rather, decreasing activity of the carbon appeared to be the primary cause. Although no specific mechanisms were identified for carbon deactivation, a loss of activity may have been related to the magnetic tape coating operation. In tape manufacturing, a resinous or polymer material is dissolved in the solvent that binds the iron oxides to the plastic film. Therefore, oligomers in the resins are potentially available to plug the activated carbon micropore structure. Also, degradation and possible polymerization of the THF may contribute to reduced carbon activity.

The deactivation of the carbon at Plant 2 was confirmed when the four-year old carbon was replaced after the repeat test period, with subsequent plant measurements indicating VOC removal efficiencies exceeding 98 percent. These results suggest a carbon life for the Plant 2 system of approximately four years.

Carbon Life and Activated Carbon Properties

The CCl_4 activity test, as described in Section 5, is the most common method for measuring the adsorptive capacity of an activated carbon. For virgin carbons, the CCl_4 activity is at a maximum and is used to approximate the micropore volume. However, with used carbon the interpretation of CCl_4 activity is somewhat imprecise, due to the presence of unknown levels of organic heel material and particulate fouling matter on the carbon. The presence of the residual material, and especially the organic heel, prevents the true measurement of carbon activity by the CCl_4 activity test alone.

The bed carbon adsorption capacity (W), can be related to measurable system parameters as mentioned in the theoretical concepts presented in Section 3. According to the Polanyi potential theory and using the Dubinin equation (Equation 3-4), the adsorption capacity (W) is related to three factors: the adsorption temperature, the bulk phase VOC concentration, and the VOC molecular volume. These three factors can be combined into a single term, the adsorption potential factor (APF), as follows:

$$\text{APF} = {\frac{T}{(V_m)(\ln C\ )}}^{2} \qquad (12\text{-}1)$$

where: T = the SLA temperature,
V_m = the solvent molar volume, and
C = the bulk phase (inlet) VOC concentration.

This form of the APF was selected because it relates directly to the forms found in the Dubinin-Radushkevich equation.

Figure 12-1 is a plot of the natural log of the adsorption capacity (W) versus the APF. As shown, the cluster of data points is relatively tight, indicating that all tested systems performed with similar adsorption capacities and operating conditions. Although the data are limited and cannot be used directly to estimate carbon life, they do indicate trends in carbon adsorption capacity. In particular, the carbon from Plant 1 and Plant 2 appeared to have the lowest adsorption capacity. This result is consistent with the low VOC removal for Plant 1 and the degradation in carbon activity and VOC control measured for Plant 2.

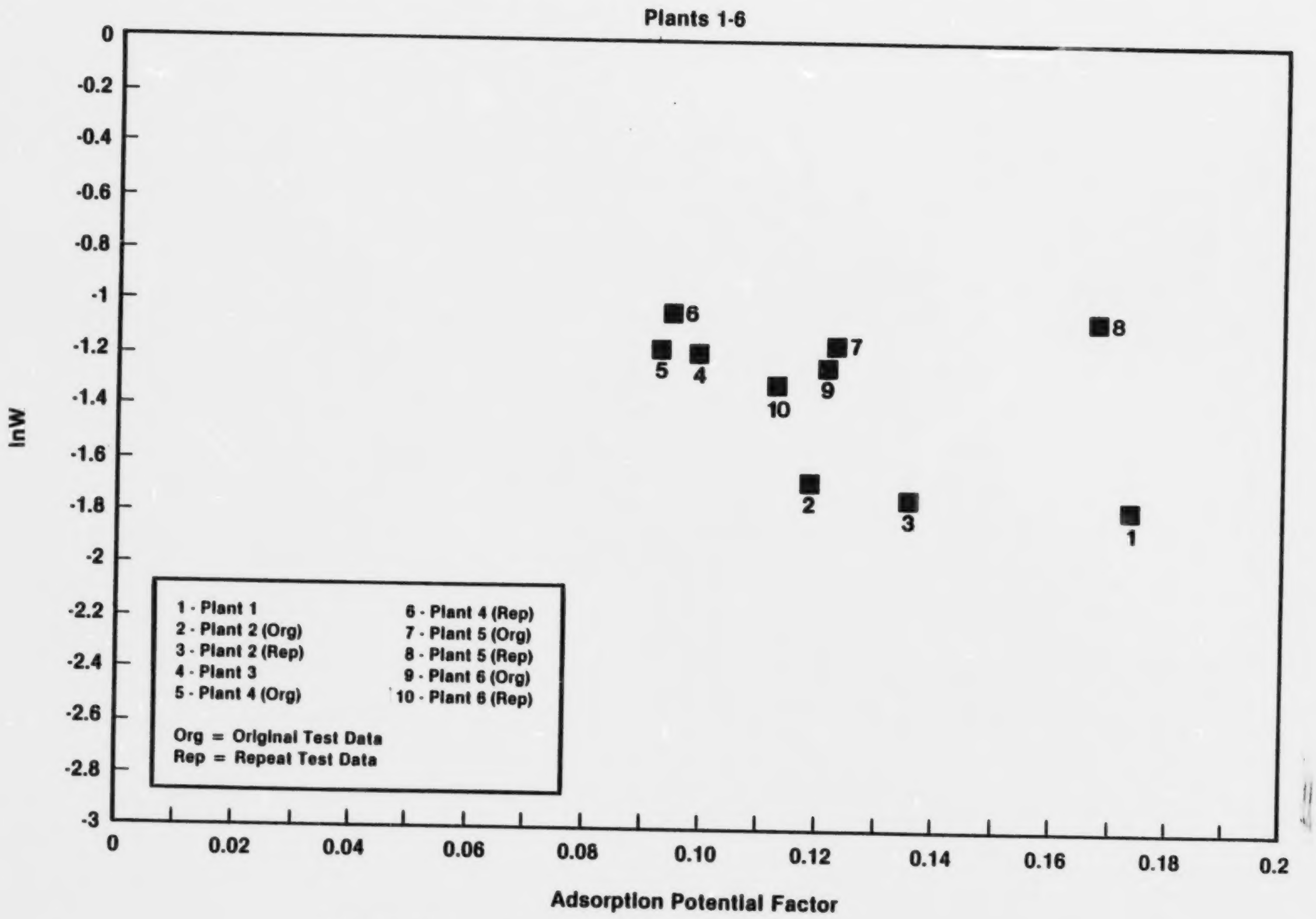

Figure 12-1. Adsorption potential versus adsorption capacity.

SECTION 13

CARBON ADSORPTION MODELING

The concept of mathematical prediction of carbon bed performance is ideal for system design and estimation of long-term performance. As with many physical processes, however, mathematical prediction of performance requires a set of complex equations that describe a number of physical phenomena or conditions that occur during adsorption, desorption, and drying/cooling. Rigorous mathematical models for carbon adsorption systems can use theoretical or empirical equations to predict the following phenomena:

- mass transfer and the rate of adsorption,
- the solvent equilibrium between the gas and solid phases,
- multicomponent interaction,
- thermal effects due to the heat of adsorption, and
- the effects of drying/cooling of the carbon.

Rigorous models of the above phenomena include non-linear partial differential equations which may be difficult to solve. The solution of these equations is usually simplified by making assumptions that limit the applicability of the models.

SINGLE COMPONENT ISOTHERM MODELS

Probably the most investigated aspect of activated carbon theory and application is the single component adsorption isotherm. Several useful and accurate models have been proposed with the Polanyi potential theory model

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probably being the most widely accepted. Polanyi's theories were significantly advanced by Dubinin and others (see Section 3, Carbon Adsorption Theory) such that the available literature contains significant data for specific carbon-solvent combinations.

Inputs to the isotherm models are few and easily measured. Generally, the models require the adsorption temperature, bulk phase concentration of the absorbate, and physical properties of the adsorbent (carbon) and adsorbate (solvent). Solution of the models is relatively straightforward, e.g., requiring the use of linear regression analysis.

MULTICOMPONENT MODELS

Prediction of the adsorption capabilities of active carbons for multicomponent systems is much more difficult than for single component systems. In the 1960's, Myers and Prausnitz presented the concept of the ideal adsorbed solution (IAS) (1). With this method, it is possible to predict mixed-gas adsorption equilibria from pure component adsorption isotherms. Myers and Prausnitz reported that the predictions of the ideal adsorption solution theory are in quantitative agreement with experimental data for a wide variety of gas mixtures and for different heterogeneous adsorbents. Use of the ideal adsorption solution model is relatively simple but does require that the pure component adsorption isotherms be measured accurately at low surface coverage (i.e., low partial pressures).

ADSORPTION MODELS

Adsorption models take into consideration the mass transfer and equilibrium characteristics of the active carbon bed. Rigorous adsorption models also take into consideration thermal effects in the carbon bed.

The most rigorous adsorption model identified is presented by Harwell, et al (2). This model accounts for multicomponent interactions, nonisothermal operation, and dynamic inlet concentrations, gas flow rates, and temperatures. Solution of the model equations is complex. The model will predict gas temperature, bed temperature, vapor-phase solvent concentration, and solid-phase solvent concentration as a function of time and position in the bed.

Another rigorous adsorption model is presented by researchers at Kansas State University (3). This model accounts for non-isothermal adsorption but is limited to a single component system. Variations of inlet concentrations were not considered, and solution of the equations is complex. The model will predict parameters similar to those predicted by the Harwell model.

A third rigorous adsorption model was developed by Ferrell, et al, (4). This multicomponent model does not consider temperature effects in the bed but presents a unique method of modeling the rate of adsorption. The model is based on a single overall mass transfer coefficient for adsorption somewhat analogous to the overall heat transfer coefficient for heat exchange. Through computer solution of the model equations, the vapor-phase solvent concentration can be predicted as a function of time.

Adsorption models have also been proposed using the concept of the mass transfer zone (MTZ). These models tend to be simplified and rely on empirical equations and breakthrough data. The results are generally only applicable to specific carbon-solvent applications.

ADSORPTION/REGENERATION MODELS

Complete models of carbon adsorption systems include characterization of the adsorption and regeneration modes. Only two adsorption/regeneration models were identified, and both are prop[illegible]ary. One model was developed by Calgon Corporation and is not available for public use. The other model was developed by Dr. Kenneth Wilde, an independent consultant, and is available for use on a national computing network (5). The Wilde model incorporates many of the concepts of the previous modelers and uses those concepts to perform a complete adsorption/regeneration analysis.

Wilde Model Specifications

Inputs to the Wilde model are extensive but are generally related to easily measurable parameters. Input data include the following:

- carbon properties (bulk density, pore volume and mean particle size);
- equilibrium isotherm data for all solvents and water vapor;
- bed dimensions;
- gas stream characteristics (flow, temperature, composition);
- mass transfer or diffusion coefficients; and,
- steam conditions for bed regeneration.

Table 13-1 lists the specific input parameters that are needed for the Wilde carbon adsorption model. Different models, such as those developed by Langmuir, Freundlich, or Dubinin-Radushkevich, can be selected for the adsorption isotherms. Also, mass transfer coefficients are needed for bulk-phase transport and transport along the carbon surface. Bulk-phase diffusion coefficients are readily available in literature (6), while surface transport coefficients are not.

The Wilde model has several input parameters for the regeneration phase. The model uses predictive techniques for regeneration outlined by other researchers (7). These techniques allow for "dead time" during the heating

TABLE 13-1. WILDE MODEL INPUT PARAMETERS

CARBON PROPERTIES	Bulk density, pore volume, particle size distribution
BED DIMENSION	Bed depth
SLA ADSORPTION CONDITIONS	Flow rate (bed volumes per hour), temperature, moisture content, solvent type, solvent concentration, adsorption time
ISOTHERM DATA	Equilibrium isotherm model type and constants (including water vapor)
SOLVENT CHARACTERISTICS	Molecular weight, liquid density, vapor pressure, diffusion coefficient (fluid and particle), heat of vaporization
REGENERATION CHARACTERISTICS	Regeneration time, steam temperature, steam rate, dead time, velocity, temperature gradient in bed
COOLING/DRYING CHARACTERISTICS	Cool time, dry time, cool/dry gas flow rate (bed volumes per hour)

period and thermal gradients in the bed during regeneration. There is also capability to predict the effects of the cooling/drying period.

The Wilde model is flexible and can provide different outputs, depending on the data requirements. The model can be used to predict breakthrough curves or solvent loading profiles in the bed. It can also be used to predict adsorption times based on a set maximum outlet concentration, average outlet concentration or removal efficiency of a particular solvent component. Conversely, the model will predict the maximum outlet concentration, average outlet concentration and specific breakthrough components for a specific adsorption time period.

In addition to predicting carbon bed system performance, the model can be used to estimate capital and operating costs of the system. The model uses data from a previous EPA study as the basis for the cost estimates (8). The cost model was not used in this study.

Modeling Carbon Bed Performance

The Wilde model was used to simulate the VOC removal capabilities of three tested carbon adsorption systems (Plants 2, 4 and 6 of the current program). Plant 2 is a magnetic tape manufacturing facility, and Plants 4 and 6 are flexible package manufacturers. These plants were chosen because of their variety of solvents, size, and operating conditions.

All inputs to the computer model (Table 13-1) were developed from test and process data generated during the test program. Adsorption isotherms were analytically determined for the specific adsorbent/adsorbate pairs for each of the plants. The isotherms were measured at the adsorption temperature of the particular system and with actual used carbon from the systems. The isotherm data were reduced to the form of the Dubinin-Radushkevich equation which is used in the computer model.

Table 13-2 shows the results of the computer modeling and compares them to the measured data. In each case, the model output was adsorption time for a specified maximum outlet concentration. The results for Plants 4 and 6 show close agreement between actual and predicted adsorption times. However, the model predicted a much longer adsorption time for Plant 2 as compared to the measured value. This result suggests that Plant 2 is potentially underperforming and, thus, showing signs of carbon degradation.

The predicted average outlet concentration for each plant was an order of magnitude lower than the actual measured value due to two reasons. First, the model does not account for elevations in outlet concentration due to a warm, moisture-laden bed coming on-line at the beginning of the adsorption cycle. However, discounting the outlet concentration increases due to incomplete bed cooling at Plants 2 and 6, the predicted average concentration and measured concentration were in good agreement. Also, the existence of fissures or short-circuiting in a bed can cause differences in the expected and measured average outlet concentration. The model does not make allowances for bed fissures and, thus, tends to predict lower outlet concentration values.

TABLE 13-2. RESULTS OF THE COMPUTER MODELING OF ACTIVATED CARBON BED SYSTEMS

	Plant 2 (Orig)		Plant 2 (Rep)		Plant 4 (Orig)		Plant 6 (Orig)	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model
Solvent	50% Toluene/50% THF		75% THF/25% Toluene		Hexane		Toluene/IPAC/NPA	
Inlet SLA, Nm^3/sec (scfm)	4.6 (9,800)		4.5 (9,500)		8.3 (17,700)		15.8 (33,400)	
Inlet VOC conc. (ppmv)	1230		1140		1280		906	
Maximum outlet conc. (ppmv)	8		144		18		73.5	
Average outlet conc.	2	0.2	40	3	11	1.1	21	3.0
Adsorption time (min)	64[a]	178	64[a]	198	120[a]	177	468	432

[a] Timed cycle

Orig = Original testing
Rep = Repeat testing
THF = Tetrahydrofuran
IPAC = Isopropyl acetate
NPA = n-Propyl acetate

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APPENDIX A

COSTING METHODOLOGY

Capital and annualized cost estimates for the six tested carbon adsorption systems were developed based upon plant data and cost engineering principles. The methodology used to develop the cost estimates is summarized in this appendix.

CAPITAL COST ESTIMATES

The basis of the capital cost estimates was information provided by the six plants, as presented in Table A-1 through A-6. In all cases, the information presented was updated to late 1983 dollars and supplemented with estimates of cost items not provided by the plants.

Costs were updated using the Chemical Engineering Plant Cost Index factors (1), as shown below:

Plant	Base Year	Index
--	1983	318
1	1975	182.4
2	1979	238.7
3	1973	144.1
4	1978	218.8
5	1976	192.1
6	1981	297.0

TABLE A-1. CAPITAL COSTS -- PLANT 1 (1975 $)

	Cost, $
DIRECT COSTS	
• Delivered equipment	250,000
• Installation materials	
-ducting	incl.
-piping	incl.
-foundations	incl.
-structures	incl.
-buildings	incl.
-electrical	incl.
-instrumentation	incl.
-insulation	incl.
-painting	incl.
-solvent storage tanks	50,000
• Installation labor	
TOTAL DIRECT COSTS (1)	300,000
INDIRECT COSTS	
• Engineering and supervision	10,000
• Miscellaneous construction expenses	18,000
• Contractor's fees	0
• Contingencies	
TOTAL INDIRECT COSTS (2)	
TOTAL FIXED CAPITAL COSTS (1 + 2)	
OTHER	
• Interest during construction	0
• Startup costs	
• Other capital items	0
TOTAL OTHER COSTS (3)	
TOTAL CAPITAL COSTS (1 + 2 + 3)	

TABLE A-2. CAPITAL COSTS -- PLANT 2 (1979 $)

	Cost, $
DIRECT COSTS	
• Delivered equipment	330,730
• Installation materials	
-ducting	incl.
-piping	incl.
-foundations	incl.
-structures	incl.
-buildings	N/A
-electrical	incl.
-instrumentation	incl.
-insulation	incl.
-painting	incl.
-solvent storage tanks	95,000
• Installation labor	incl.
TOTAL DIRECT COSTS (1)	425,730
INDIRECT COSTS	
• Engineering and supervision	
• Miscellaneous construction expenses	
• Contractor's fees	
• Contingencies	
TOTAL INDIRECT COSTS (2)	
TOTAL FIXED CAPITAL COSTS (1 + 2)	
OTHER	
• Interest during construction	
• Startup costs	
• Other capital items	
TOTAL OTHER COSTS (3)	
TOTAL CAPITAL COSTS (1 + 2 + 3)	

TABLE A-3. CAPITAL COSTS -- PLANT 3 (1973 $)

	Cost, $
DIRECT COSTS	
• Delivered equipment	incl.
• Installation materials	
-ducting	incl.
-piping	incl.
-foundations	incl.
-structures	incl.
-buildings	incl.
-electrical	incl.
-instrumentation	incl.
-insulation	incl.
-painting	incl.
-solvent storage tanks	incl.
• Installation labor	incl.
TOTAL DIRECT COSTS (1)	INCL.
INDIRECT COSTS	
• Engineering and supervision	incl.
• Miscellaneous construction expenses	incl.
• Contractor's fees	incl.
• Contingencies	incl.
TOTAL INDIRECT COSTS (2)	INCL.
TOTAL FIXED CAPITAL COSTS (1 + 2)	INCL.
OTHER	
• Interest during construction	incl.
• Startup costs	incl.
• Other capital items	incl.
TOTAL OTHER COSTS (3)	INCL.
TOTAL CAPITAL COSTS (1 + 2 + 3)	850,000

TABLE A-4. CAPITAL COSTS -- PLANT 4 (1978 $)

	Cost, $
DIRECT COSTS	
• Delivered equipment	523,275
• Installation materials	
-ducting	incl.
-piping	70,600
-foundations	41,174
-structures	incl.
-buildings	10,631
-electrical	8,011
-instrumentation	incl.
-insulation	18,040
-painting	incl.
-solvent storage tanks	incl.
• Installation labor	148,456
TOTAL DIRECT COSTS (1)	784,995
INDIRECT COSTS	
• Engineering and supervision	89,089
• Miscellaneous construction expenses	incl.
• Contractor's fees	incl.
• Contingencies	
TOTAL INDIRECT COSTS (2)	
TOTAL FIXED CAPITAL COSTS (1 + 2)	
OTHER	
• Interest during construction	
• Startup costs	
• Other capital items	
TOTAL OTHER COSTS (3)	
TOTAL CAPITAL COSTS (1 + 2 + 3)	

TABLE A-5. CAPITAL COSTS -- PLANT 5 (1976 $)

	Cost, $
DIRECT COSTS	
• Delivered equipment	88,872
• Installation materials	
-ducting	incl.
-piping	22,142
-foundations	incl.
-structures	incl.
-buildings	25,000
-electrical	incl.
-instrumentation	incl.
-insulation	incl.
-painting	incl.
-solvent storage tanks	incl.
• Installation labor	
TOTAL DIRECT COSTS (1)	
INDIRECT COSTS	
• Engineering and supervision	
• Miscellaneous construction expenses	
• Contractor's fees	
• Contingencies	
TOTAL INDIRECT COSTS (2)	
TOTAL FIXED CAPITAL COSTS (1 + 2)	
OTHER	
• Interest during construction	
• Startup costs	
• Other capital items	
TOTAL OTHER COSTS (3)	
TOTAL CAPITAL COSTS (1 + 2 + 3)	

TABLE A-6. CAPITAL COSTS -- PLANT 6 (1981 $)

	Cost, $
DIRECT COSTS	
• Delivered equipment	2,090,308
• Installation materials	
-ducting	incl.
-piping	incl.
-foundations	incl.
-structures	incl.
-buildings	17,313
-electrical	incl.
-instrumentation	incl.
-insulation	incl.
-painting	incl.
-solvent storage tanks	incl.
• Installation labor	incl.
TOTAL DIRECT COSTS (1)	2,107,621
INDIRECT COSTS	
• Engineering and supervision	51,000
• Miscellaneous construction expenses	179,996
• Contractor's fees	incl.
• Contingencies	138,000
TOTAL INDIRECT COSTS (2)	368,996
TOTAL FIXED CAPITAL COSTS (1 + 2)	2,476,617
OTHER	
• Interest during construction	
• Startup costs	29,808
• Other capital items	
TOTAL OTHER COSTS (3)	
TOTAL CAPITAL COSTS (1 + 2 + 3)	

The reported costs were updated by multiplying by the capital cost factor, which is defined as the ratio of the 1983 index to the appropriate base year index.

Capital cost items not reported by the plants were estimated based upon the following:

- installation labor (Plant 5) -- 25 percent of the installation materials (2,3);
- engineering and supervision (Plants 2 and 5) -- 5 percent of the total direct costs, based upon the average of the reported data;
- miscellaneous construction expenses and contractors' fees (Plants 1, 2 and 5) -- assumed to be negligible or included in installation costs if not reported;
- contingencies (Plants 1, 2 and 4) -- 4 percent of the total direct cost for Plants 1 and 2 based on Plant 6 data and negligible for Plant 4 due to precision of estimate;
- interest during construction (Plants 1, 2, 4, 5 and 6) -- assumed to be negligible due to relatively simple construction; and,
- startup (Plants 1, 2, 4 and 5) -- 5 percent of the total fixed capital cost (4).

ANNUALIZED COST ESTIMATES

Information provided by the plants, presented in Tables A-7 through A-12, was used as the basis of the annualized cost estimates. The reported cost data were supplemented with estimates of data not reported, as outlined below:

- labor rates (Plant 3) -- estimated based upon data reported for the other plants;

- labor unit costs (Plants 2, 3, 4 and 5) -- estimated from earlier data (4);

- maintenance materials (Plants 1, 2, 3 and 4) -- 1 percent of total direct cost, estimated from Plants 5 and 6;

- activated carbon (Plants 2, 5 and 6) -- estimated based upon expected carbon life and data reported for Plant 1;

- steam unit costs (Plant 1) -- based upon the average of the data reported for the other plants;

- cooling water unit costs (Plants 2, 3, 4 and 5) -- \$0.20/1,000 gal. (4);

- chilled water unit costs (Plant 1) -- \$2.00/1,000 gal (twice the unit cost for Plant 1 cooling water);

- capital recovery (Plants 1, 2, 3, 4, 5 and 6) -- calculated as:

$$CR = TCC \times \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

TABLE A- 7 . ANNUAL OPERATING COSTS -- PLANT 1 (1983 $)

DIRECT COSTS	Rate	Unit Cost
• Labor		
-operating	40 m-hr/wk	$ 10.40/hr
-maintenance	10 m-hr/wk	$ 10.40/hr
-laboratory	0 m-hr/wk	$ N/A /hr
-supervisory	4 m-hr/wk	$ 20.00/hr
• Maintenance materials		$ /yr
• Activated carbon (average life = 1 yr)	$ 12,000 /total replacement	$ /lb
• Utilities		
-electricity	5,000 kwh/wk	$ 0.07 /kwh
-steam	1,600 lb/hr	$ /1000 lbs
-cooling water	600 gpm[a]	$ 1.00 /1000 gal
-chilled water	40 gpm[a]	$ /1000 gal
TOTAL DIRECT COSTS (1)		
INDIRECT COSTS		
• Labor overhead		$ /yr
• General and administrative		$ /yr
• Insurance and property taxes		$ /yr
TOTAL INDIRECT COSTS (2)		$
TOTAL ANNUAL OPERATING COSTS[b] (1 + 2)		$

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[a] Refers to total usage rate, not make-up requirements (as reflected by unit costs).

[b] Excluding capital recovery.

TABLE A- 8 . ANNUAL OPERATING COSTS -- PLANT 2 (1983 $)

DIRECT COSTS	Rate	Unit Cost
• Labor		
-operating	m-hr/wk	$ /hr
-maintenance	m-hr/wk	$ /hr
-laboratory	m-hr/wk	$ /hr
-supervisory	m-hr/wk	$ /hr
• Maintenance materials		$ /yr
• Activated carbon (average life = yr)	$ /total replacement	$ /lb
• Utilities		
-electricity	4,000 kwh/wk	$ 0.05 /kwh
-steam	1,000 lb/hr	($5,000/mo.)/1000 lbs
-cooling water	220 gpm[a]	/1000 gal
-chilled water	0 gpm	/1000 gal
TOTAL DIRECT COSTS (1)		
INDIRECT COSTS		
• Labor overhead		$ /yr
• General and administrative		$ /yr
• Insurance and property taxes		$ /yr
TOTAL INDIRECT COSTS (2)		
TOTAL ANNUAL OPERATING COSTS[b] (1 + 2)		

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[a] Refers to total usage rate, not make-up requirements (as reflected by unit costs).

[b] Excluding capital recovery.

TABLE A- 9 . ANNUAL OPERATING COSTS -- PLANT 3 (1983 $)

	Rate	Unit Cost
DIRECT COSTS		
• Labor		
-operating	176 m-hr/wk	$ 8.69 /hr
-maintenance	40 m-hr/wk	$ 8.85 /hr
-laboratory	0 m-hr/wk	$ /hr
-supervisory	60 m-hr/wk	$ /hr
• Maintenance materials		$ /yr
• Activated carbon (average life = 0.75 yr)	$ 42,120 /total replacement	$ 1.62 /lb
• Utilities		
-electricity	18,000 kwh/wk	$ 0.077/kwh
-steam	9,000 lb/hr	$ 8.00 /1000 lbs
-cooling water	1,500 gpm[a]	/1000 gal
-chilled water	0 gpm	/1000 gal
TOTAL DIRECT COSTS (1)		
INDIRECT COSTS		
• Labor overhead		$ 46,000/yr
• General and administrative		$ 28,000/yr
• Insurance and property taxes		$ /yr
TOTAL INDIRECT COSTS (2)		
TOTAL ANNUAL OPERATING COSTS[b] (1 + 2)		

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[a] Refers to total usage rate, not make-up requirements (as reflected by unit costs).

[b] Excluding capital recovery.

TABLE A-10. ANNUAL OPERATING COSTS -- PLANT 4 (1983 $)

	Rate	Unit Cost
DIRECT COSTS		
• Labor		
-operating	25 m-hr/wk	$ /hr
-maintenance	15 m-hr/wk	$ /hr
-laboratory	0 m-hr/wk	$ /hr
-supervisory	2 m-hr/wk	$ /hr
• Maintenance materials		$ /yr
• Activated carbon (average life = 3-5 yr)	$ 30,750/total replacement	$ 1.53/lb
• Utilities		
-electricity	10,000 kwh/wk	$ 0.058/kwh
-steam	2,000 lb/hr	$ 7.50/1000 lbs
-cooling water	570 gpm[a]	/1000 gal
-chilled water	0 gpm	N/A /1000 gal
TOTAL DIRECT COSTS (1)		
INDIRECT COSTS		
• Labor overhead		$ /yr
• General and administrative		$ /yr
• Insurance and property taxes		$ /yr
TOTAL INDIRECT COSTS (2)		
TOTAL ANNUAL OPERATING COSTS[b] (1 + 2)		

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[a] Refers to total usage rate, not make-up requirements (as reflected by unit costs).

[b] Excluding capital recovery.

TABLE A-11. ANNUAL OPERATING COSTS -- PLANT 5 (1983 $)

	Rate	Unit Cost
DIRECT COSTS		
• Labor		
-operating	0 m-hr/wk	$ /hr
-maintenance	2 m-hr/wk	$ 40 /hr
-laboratory	0 m-hr/wk	$ /hr
-supervisory	5 m-hr/wk	$ 125 /hr
• Maintenance materials		$1,000 /yr
• Activated carbon (average life = yr)	$ /total replacement	$ /lb
• Utilities		
-electricity	4,000 kwh/wk	$ 0.09 /kwh
-steam	3,000 lb/hr	$ 3.61 /1000 lbs
-cooling water	150 gpm	/1000 gal
-chilled water	0 gpm	N/A /1000 gal
TOTAL DIRECT COSTS (1)		
INDIRECT COSTS		
• Labor overhead		$ /yr
• General and administrative		$ /yr
• Insurance and property taxes		$ /yr
TOTAL INDIRECT COSTS (2)		
TOTAL ANNUAL OPERATING COSTS[a] (1 + 2)		

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[a] Excluding capital recovery.

TABLE A-12. ANNUAL OPERATING COSTS -- PLANT 6 (1983 $)

	Rate	Unit Cost
DIRECT COSTS		
• Labor		
-operating	88 m-hr/wk	$ 22 /hr
-maintenance	9 m-hr/wk	$ 20 /hr
-laboratory	16 m-hr/wk	$ 18 /hr
-supervisory	18 m-hr/wk	$ 29 /hr
• Maintenance materials		$ 37,432/yr
• Activated carbon (average life = yr)	$ /total replacement	$ /lb
• Utilities		
-electricity	20,000 kwh/wk	$ 0.0403/kwh
-steam	1,200 lb/hr	$ 4.416 /1000 lbs
-cooling water	2,500 gpm	$ 1.34 /1000 gal
-chilled water	0 gpm	/1000 gal
TOTAL DIRECT COSTS (1)		
INDIRECT COSTS		
• Labor overhead		$ /yr
• General and administrative		$ /yr
• Insurance and property taxes		$ /yr
TOTAL INDIRECT COSTS (2)		
TOTAL ANNUAL OPERATING COSTS[a] (1 + 2)		

[a] Excluding capital recovery.

where: TCC = total capital cost

i = interest rate = 0.10

n = equipment life = 10 years

- labor and plant overload (Plants 1, 2, 4, 5 and 6) -- calculated as 0.75 (labor cost) + 0.25 (maintenance materials), except for Plants 5 and 6, which included labor overhead in the reported labor unit costs (4);

- general and administrative (Plants 1, 2, 4, 5 and 6) -- 1 percent of total fixed capital cost (4); and,

- insurance and property tax (Plants 1, 2, 3, 4, 5 and 6) -- 2.5 percent of the total fixed capital cost (4).

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